

# Surveying the Cosmic Microwave Background from



ACTPol to CMB-S4

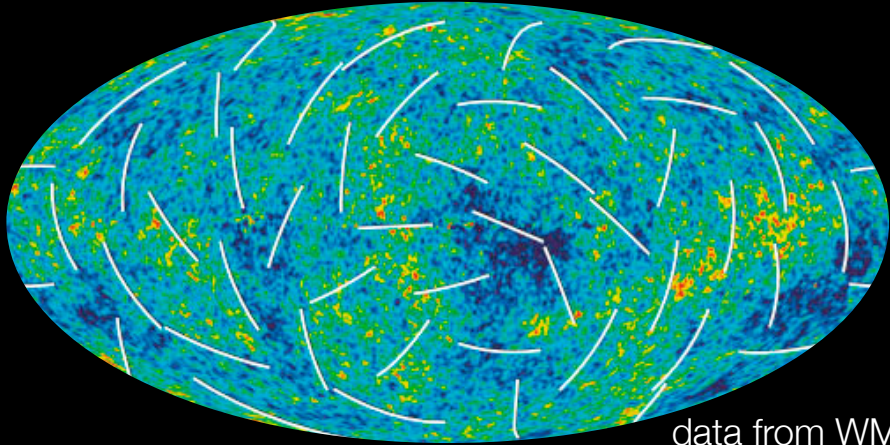
Jeff McMahon





# Cosmological Measurements with the CMB

## CMB anisotropy

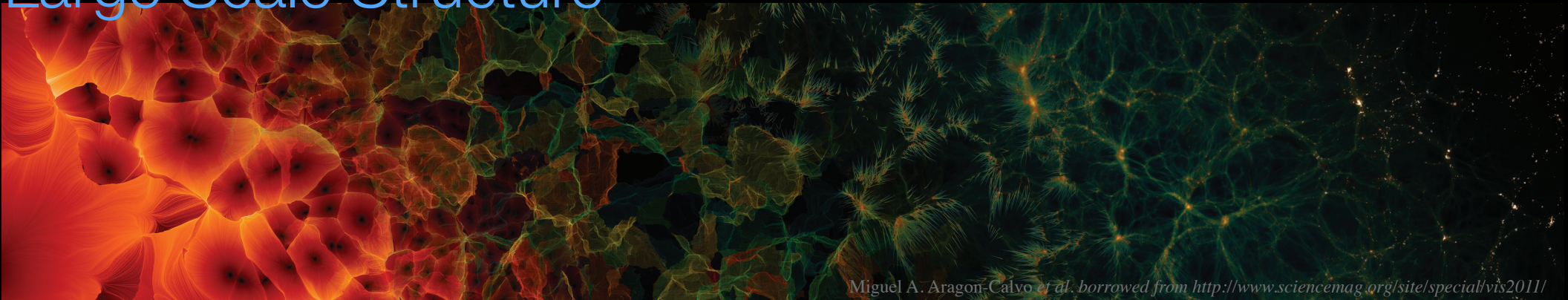


data from WMAP

Snapshot of our universe  
at 380,000 years

carries the imprint of inflationary  
parameters, the number of light  
relativistic species, and more

## Large Scale Structure



Miguel A. Aragon-Calvo *et al.* borrowed from <http://www.sciencemag.org/site/special/vis2011/>

Probes our universe from age  $\sim 1$  to  $\sim 13.8$  Billion Years

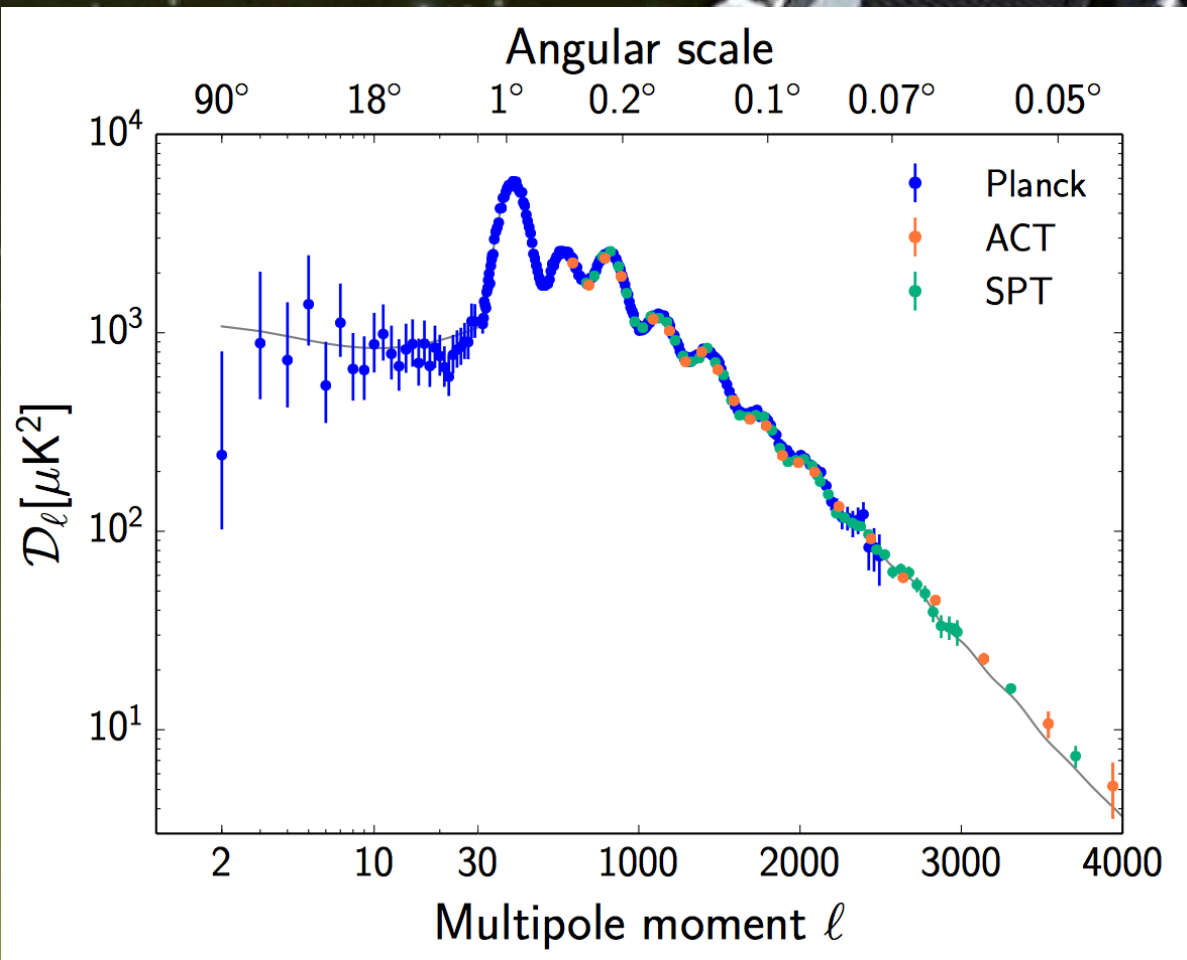
sensitive to dark energy and dark matter (neutrinos), and other  
parameters.



# CMB Power Spectrum

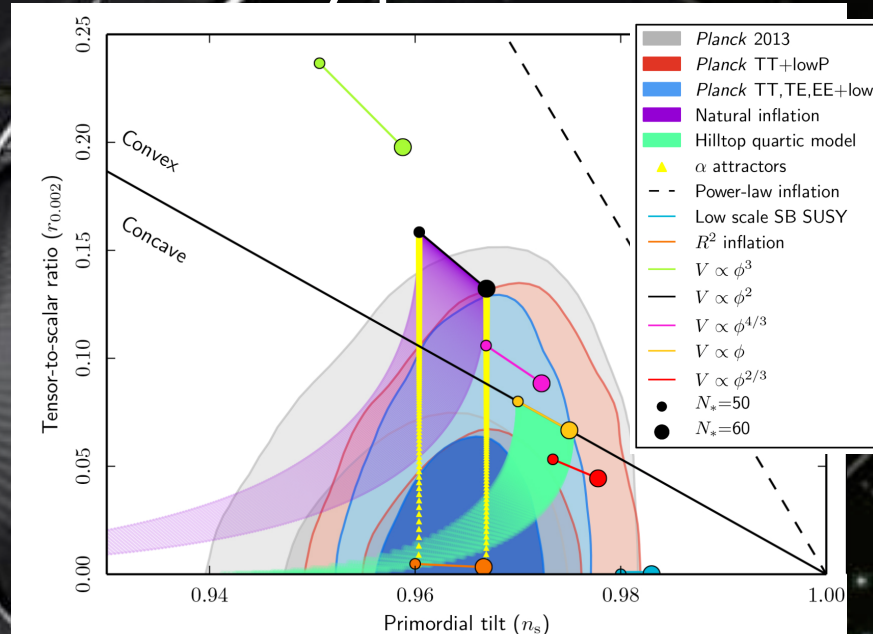
from Planck 2015 results papers XI, XII, and XX

Temperature power spectrum

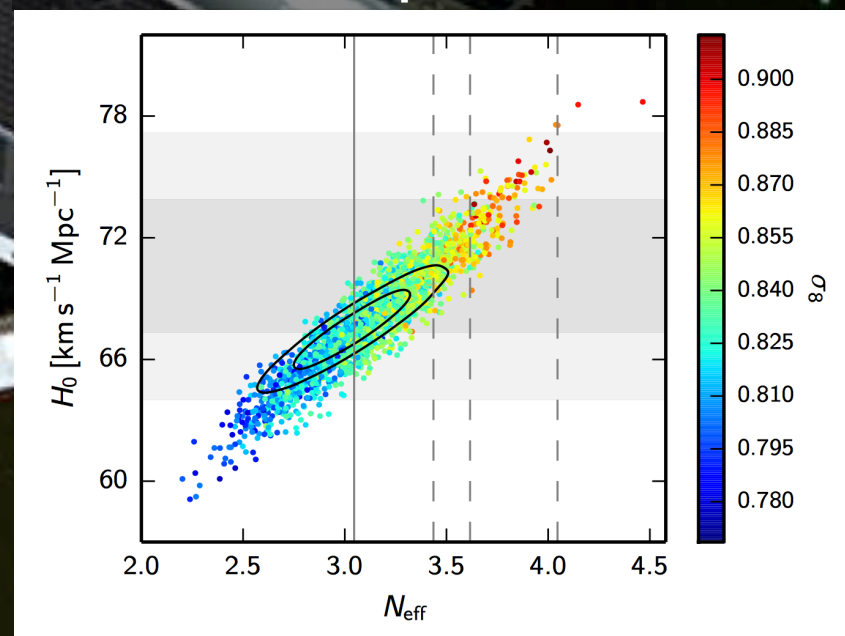


Next Frontier: Polarization

inflationary parameters



neutrino species

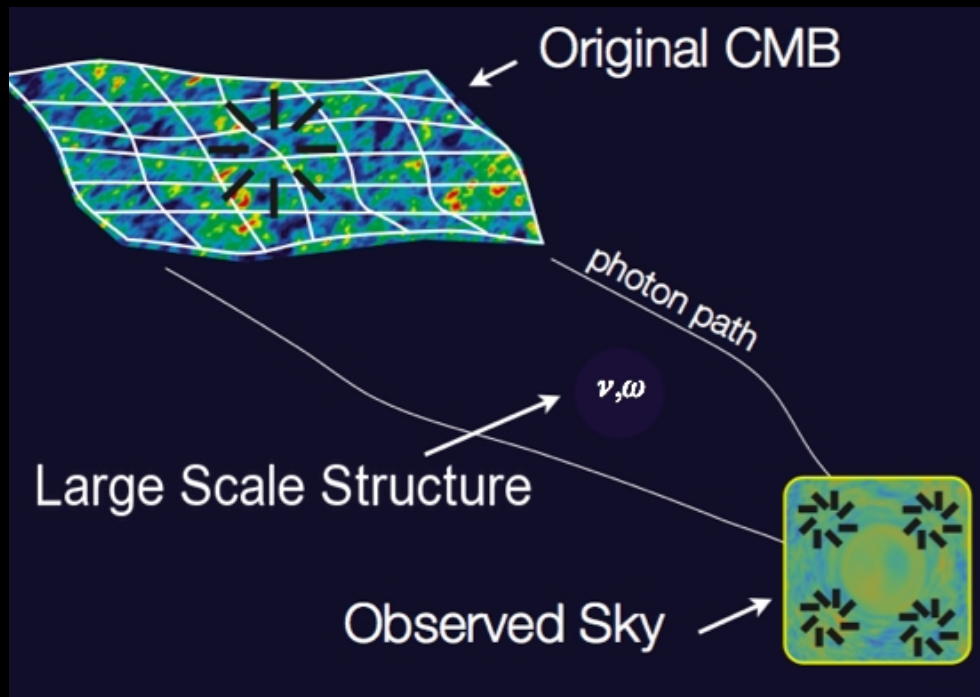




# Large Scale Structure with Galaxy Clusters and Weak Lensing

Miguel A. Aragon-Calvo *et al.* borrowed from <http://www.sciencemag.org/site/special/vis2011/>

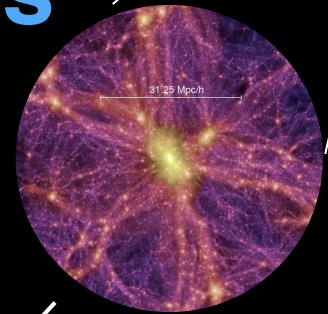
## CMB gravitational lensing



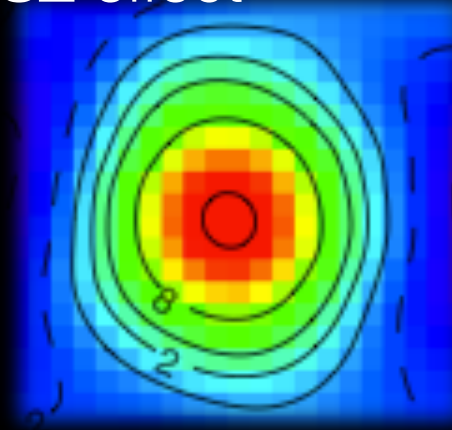
Leverage through cross-correlations with optical surveys

## SZ Clusters

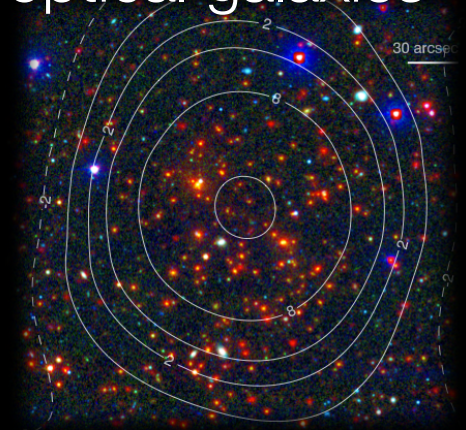
Prediction:  
dark matter  
halos



Measurements:  
SZ effect



optical galaxies



also x-ray, galaxy weak-lensing,  
velocity dispersion, and others

Large scale structure constrains **neutrino masses, dark energy**, and a other physics

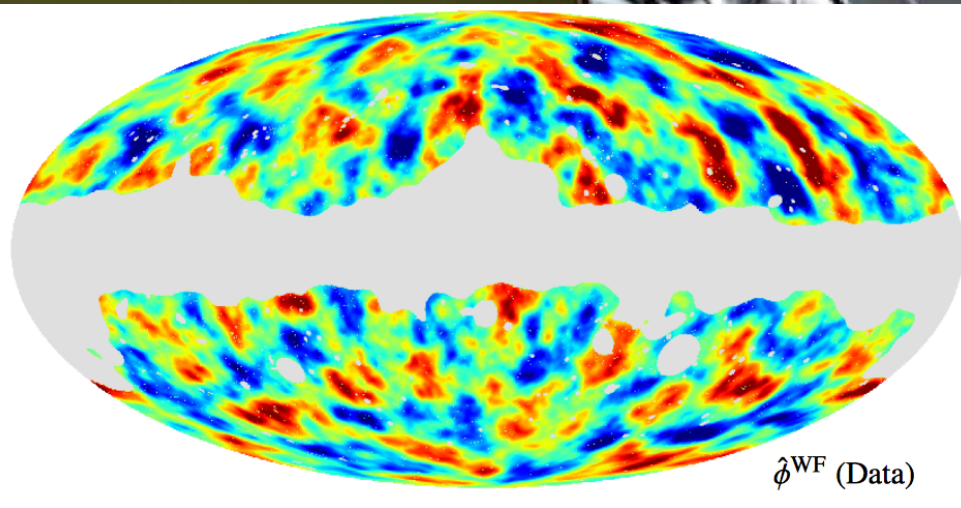


# CMB Lensing

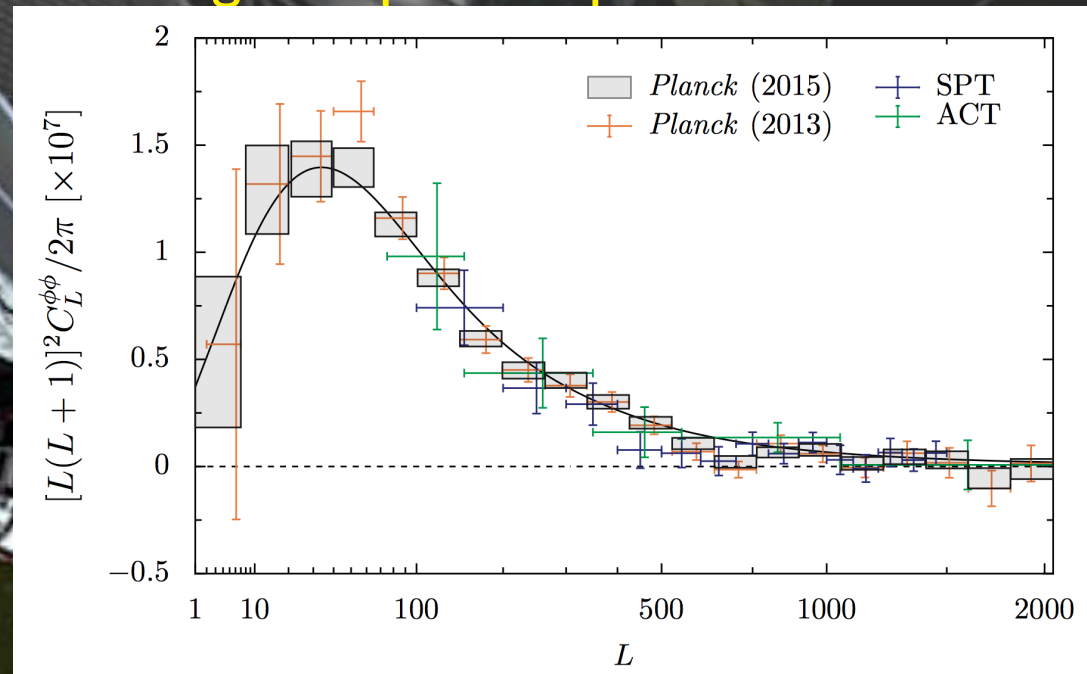
see *Planck 2015 Results Paper XV and XIII*

- 40  $\sigma$  detection
- percent level constraints on curvature and dark energy
- limits  $\sum m_\nu < 0.68$  eV from lensing alone,  $< 0.2$  from a combination of measurements
- demonstrated power of cross correlations (CIB, other examples)
- CMB lensing is rapidly maturing -- more sensitivity needed

## Lensing Reconstruction

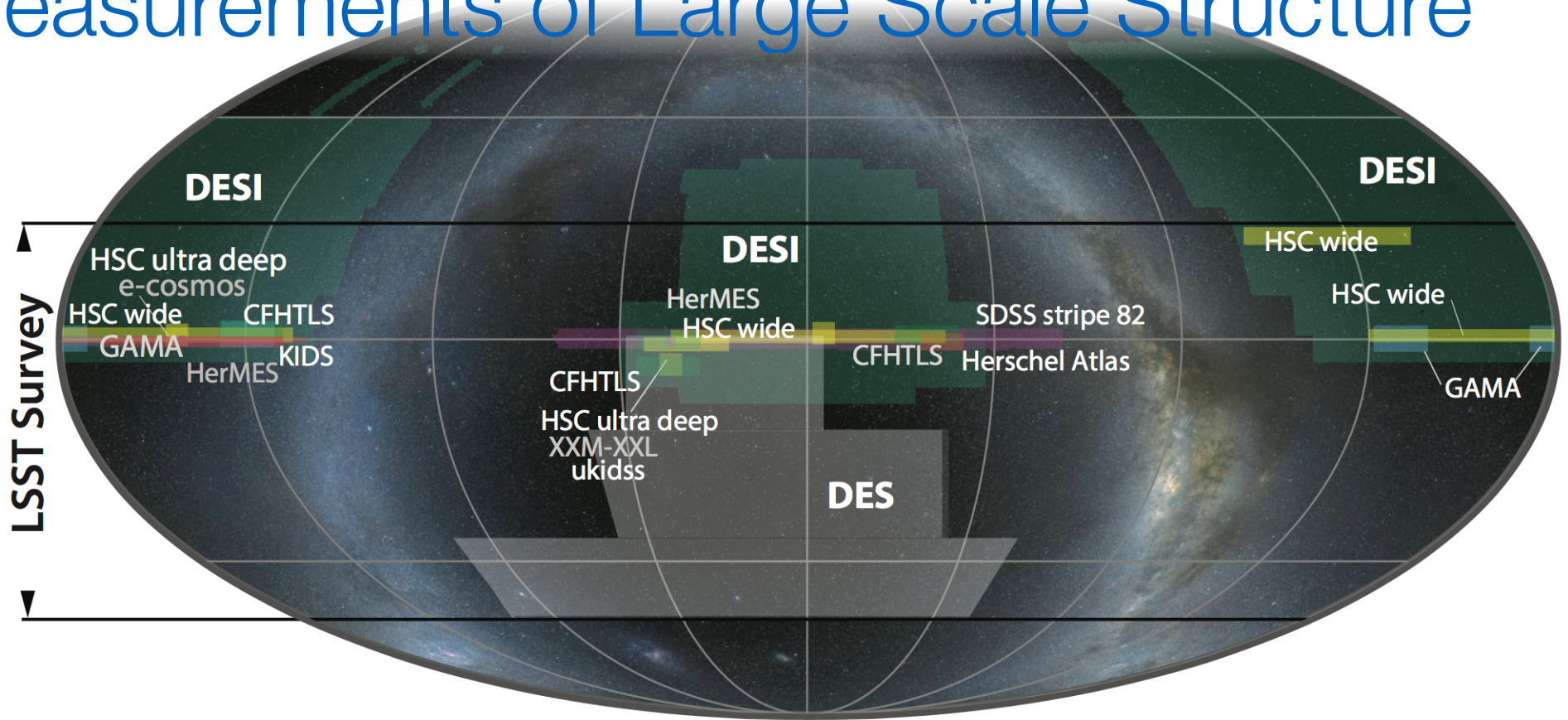


## Convergence power spectrum





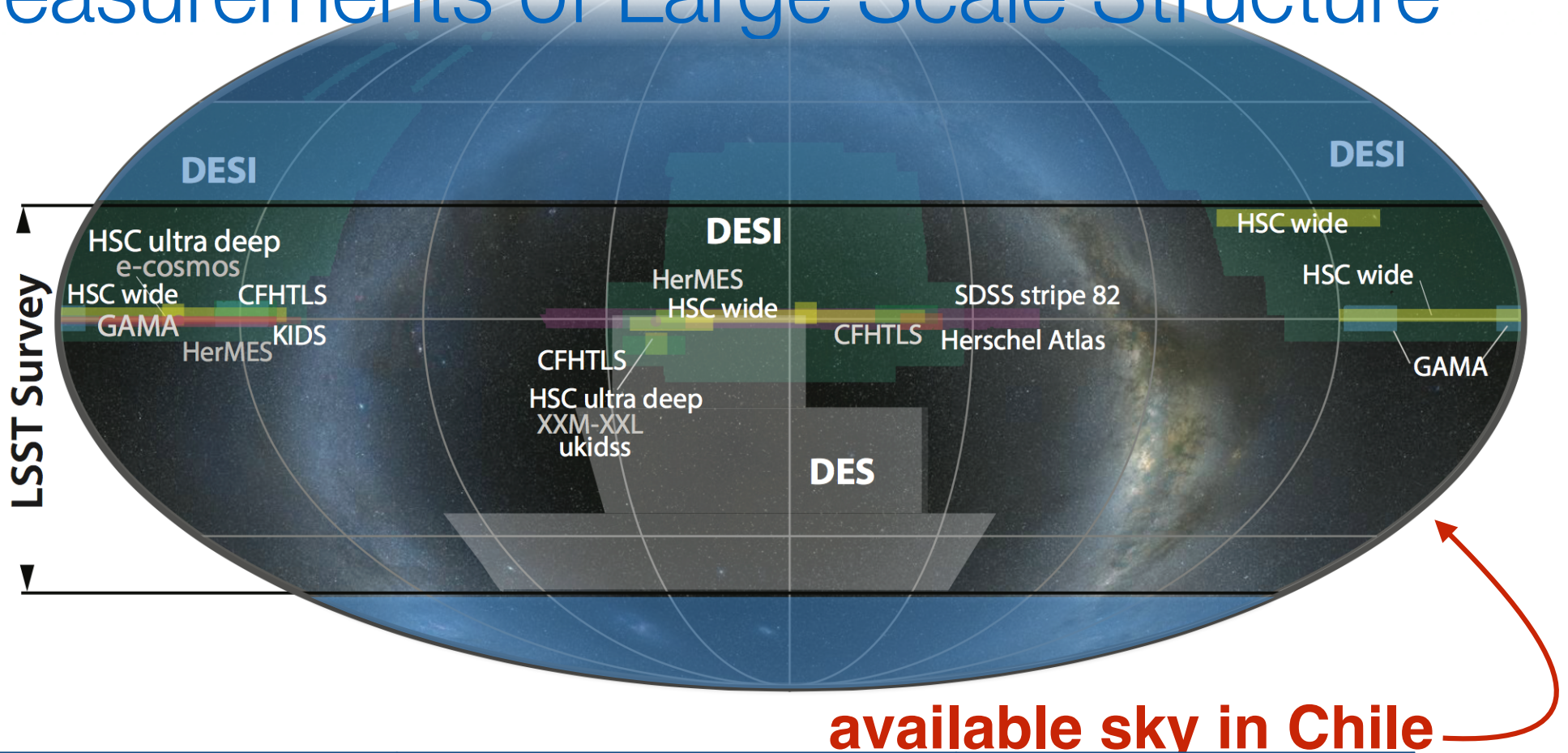
# Cross-correlations with optical measurements of Large Scale Structure



survey type	measurements	complementarity
photometric surveys	clusters	clusters tSZ, scaling relations, mass calibration (CMB lensing)
spectroscopic surveys	matter power spectrum / BAO	velocity field (kSZ), calibration
galaxy shear lensing	matter power spectrum	calibration of multiplicative bias



# Cross-correlations with optical measurements of Large Scale Structure



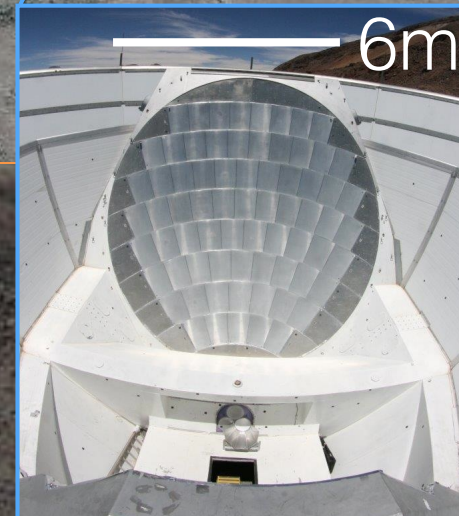
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## Chile



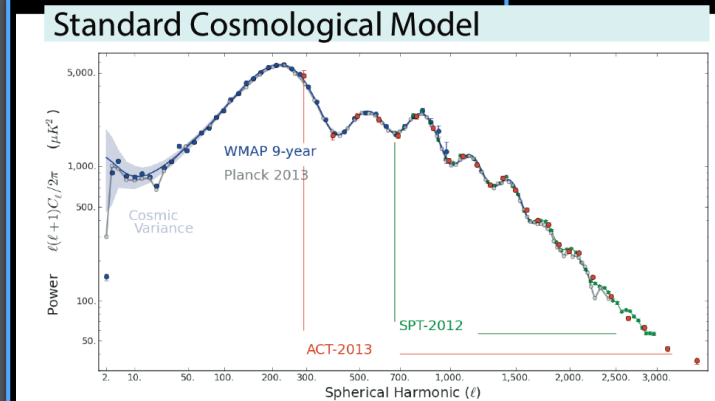
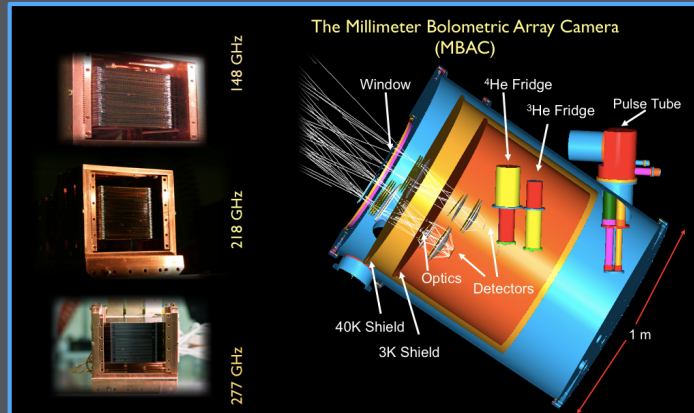
- 5200 m (high)
- Desert (dry)
- Latitude  $-23^{\circ}$





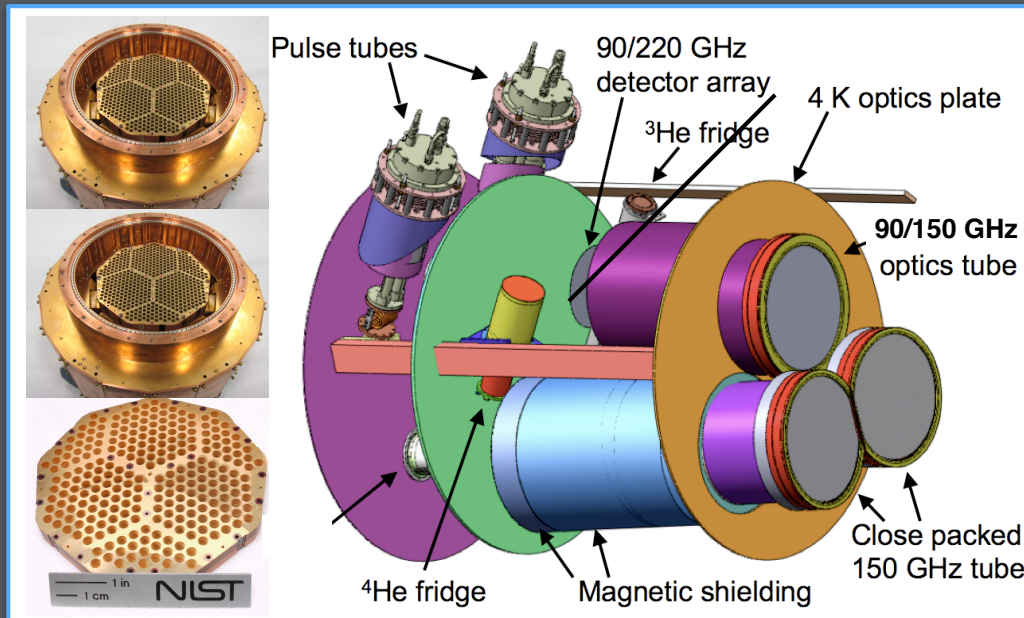
# ACT Cameras and future instruments

The Past:  
2007-2010  
**MBAC**

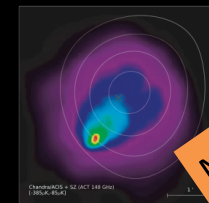


**ACT**  
discovery  
highlights

The Present:  
2012-2015  
**ACTPol**

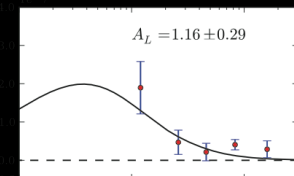


Sunyaev-Zel'dovich Effect



Most massive at  $t/2$ !

Gravitational Lensing



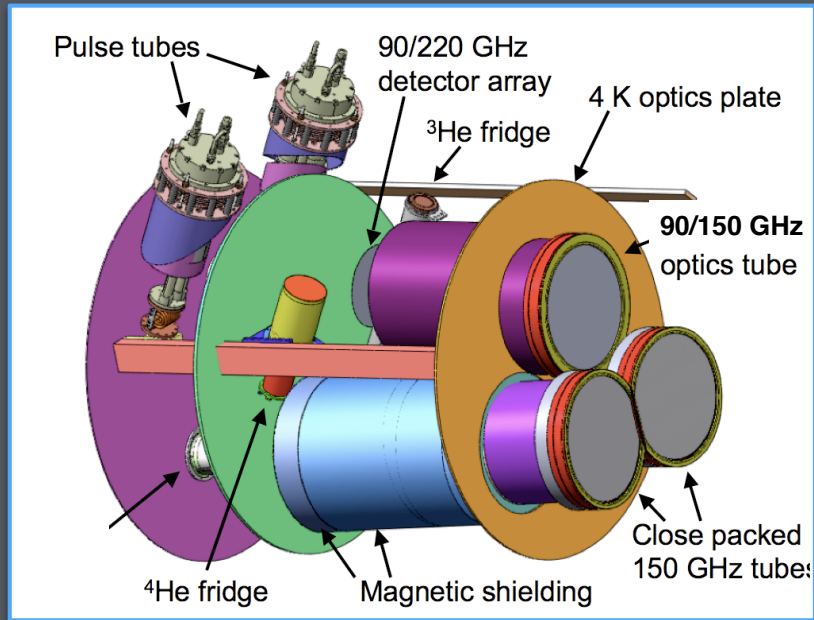
FIRST!

The Future:  
2016-2019 **Advanced ACTPol (AdvACT)**

2020 and beyond  
**Simons**  
**Observatory**  
**CMB-S4**



# the ACTPol Receiver



## 3 optics tubes

- 2 @ 150 GHz arrays
- 1 @ 90/150 multichroic

## Metamaterial AR silicon lenses

- low reflectance
- low dielectric loss

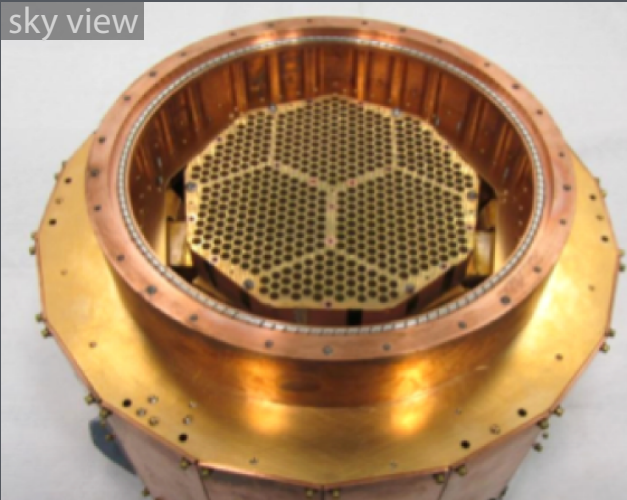
## Dilution refrigerator

- 90 mK base
- continuous operation



## Detector Arrays

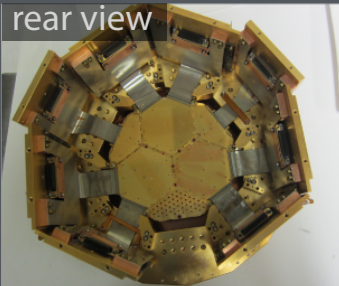
sky view



detector wafer

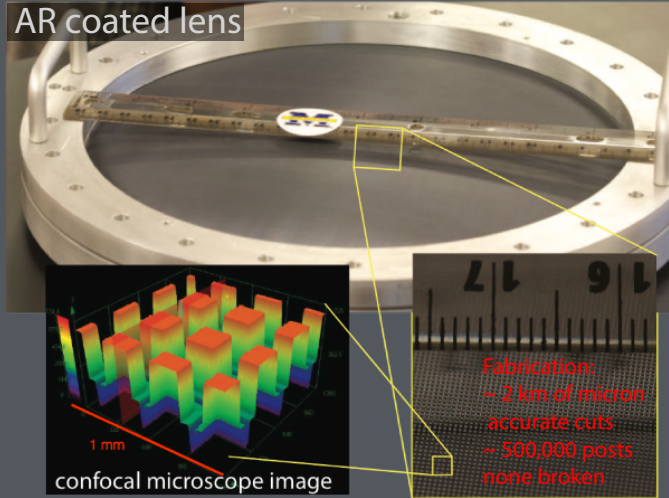


rear view



## Metamaterial AR Coated Silicon Lenses

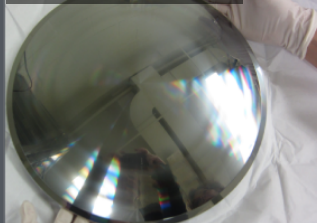
AR coated lens



three layer coating

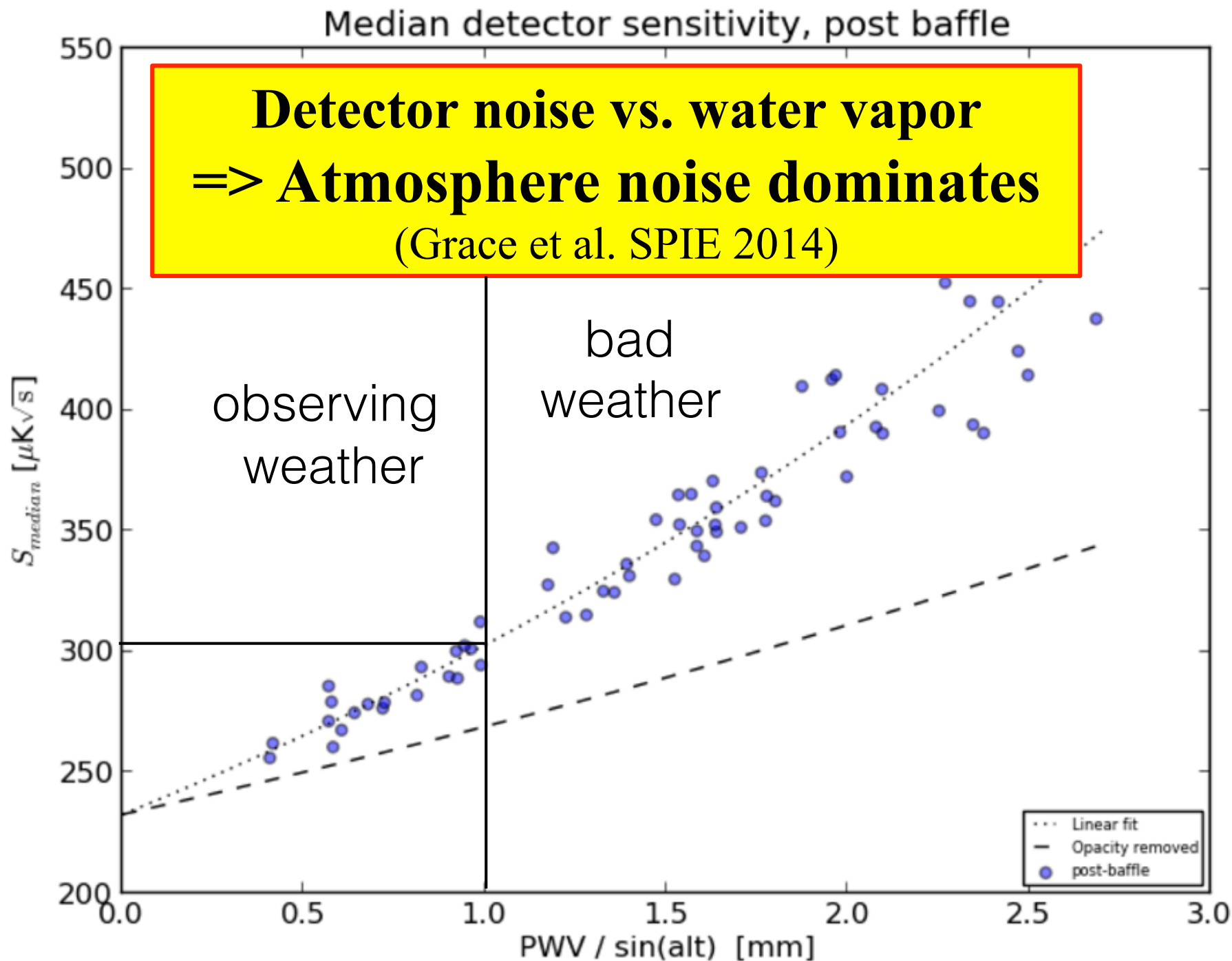


uncoated lens





Detector noise ( $\mu\text{K s}^{1/2}$ )

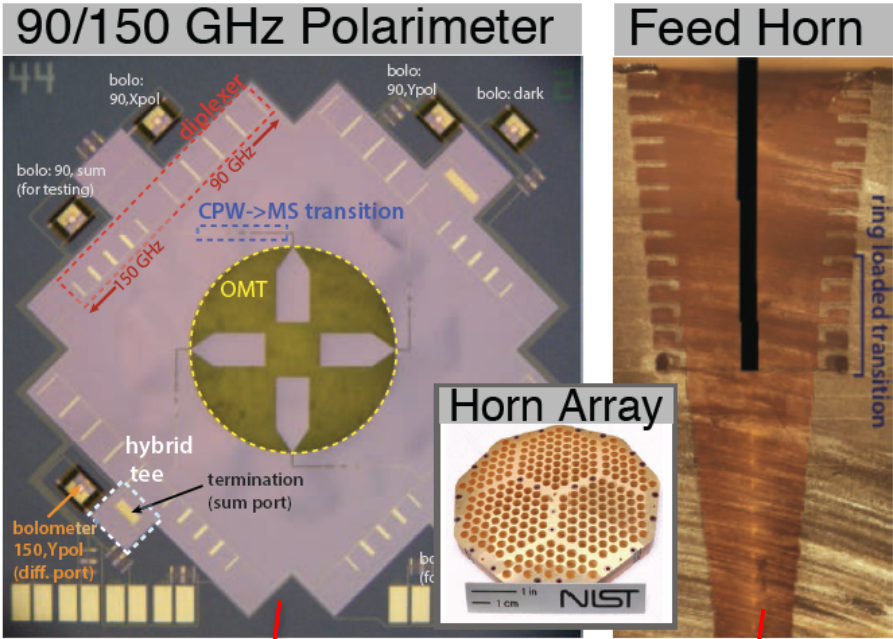


Elevation corrected water vapor (mm)

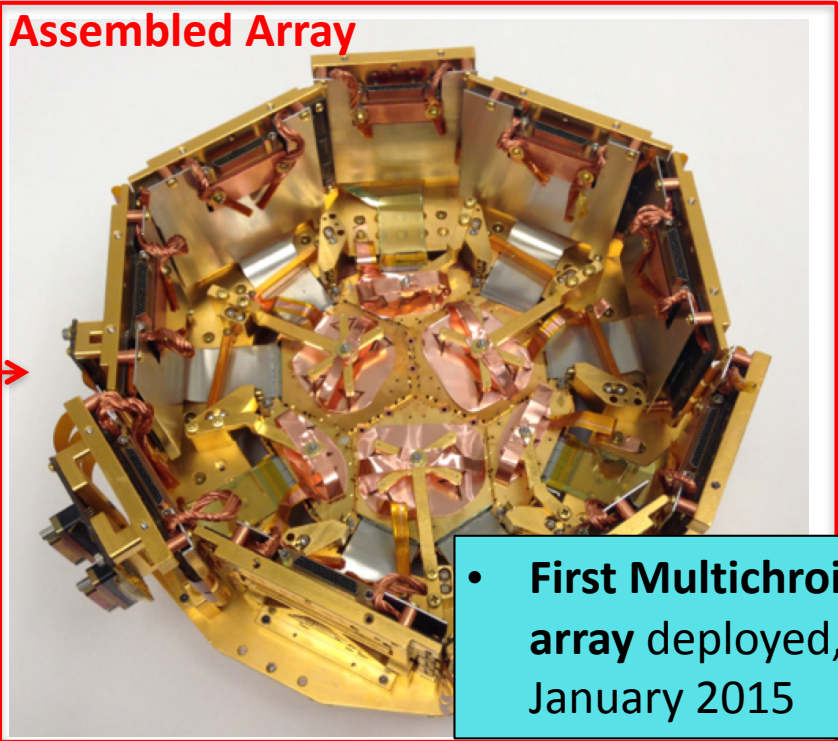
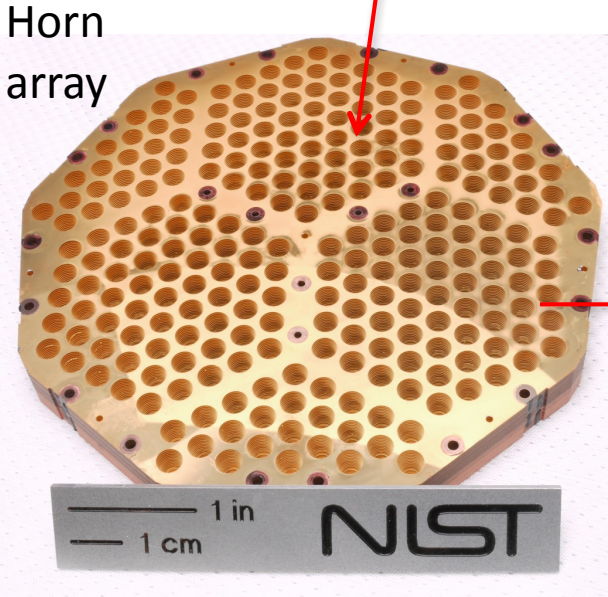
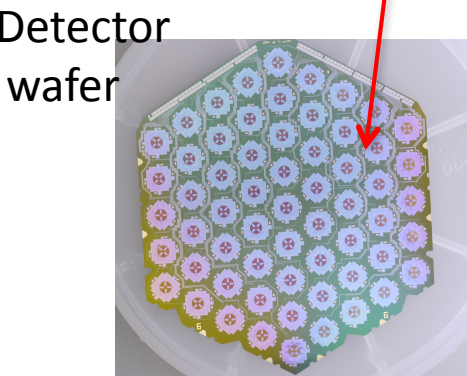
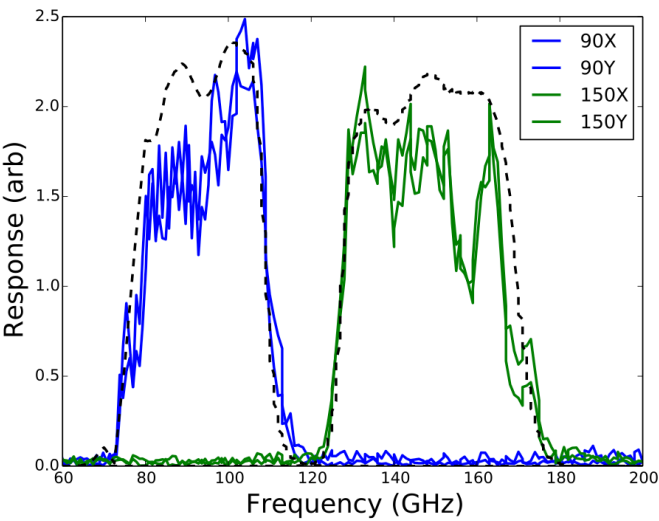


# ACTPol Multichroic Polarimeter Array

- New dichroic polarimeters
- Datta et al., JLTP (2014)



sensitive to the **90 GHz** and **146 GHz** CMB bands in each pixel



- **First Multichroic array deployed, January 2015**



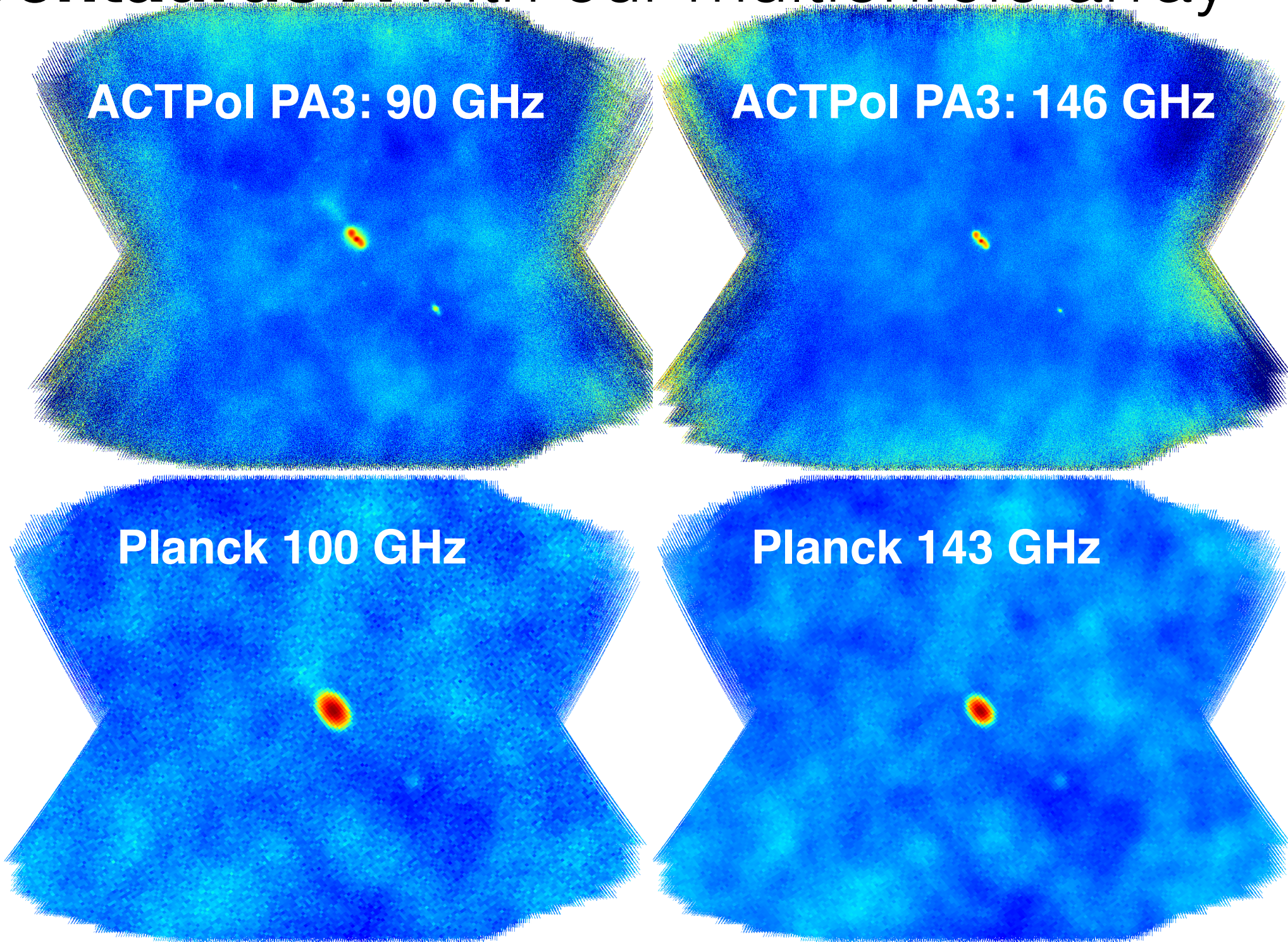
# **Centaurus A** with our multichroic array

**ACTPol PA3: 90 GHz**

**ACTPol PA3: 146 GHz**

**Planck 100 GHz**

**Planck 143 GHz**





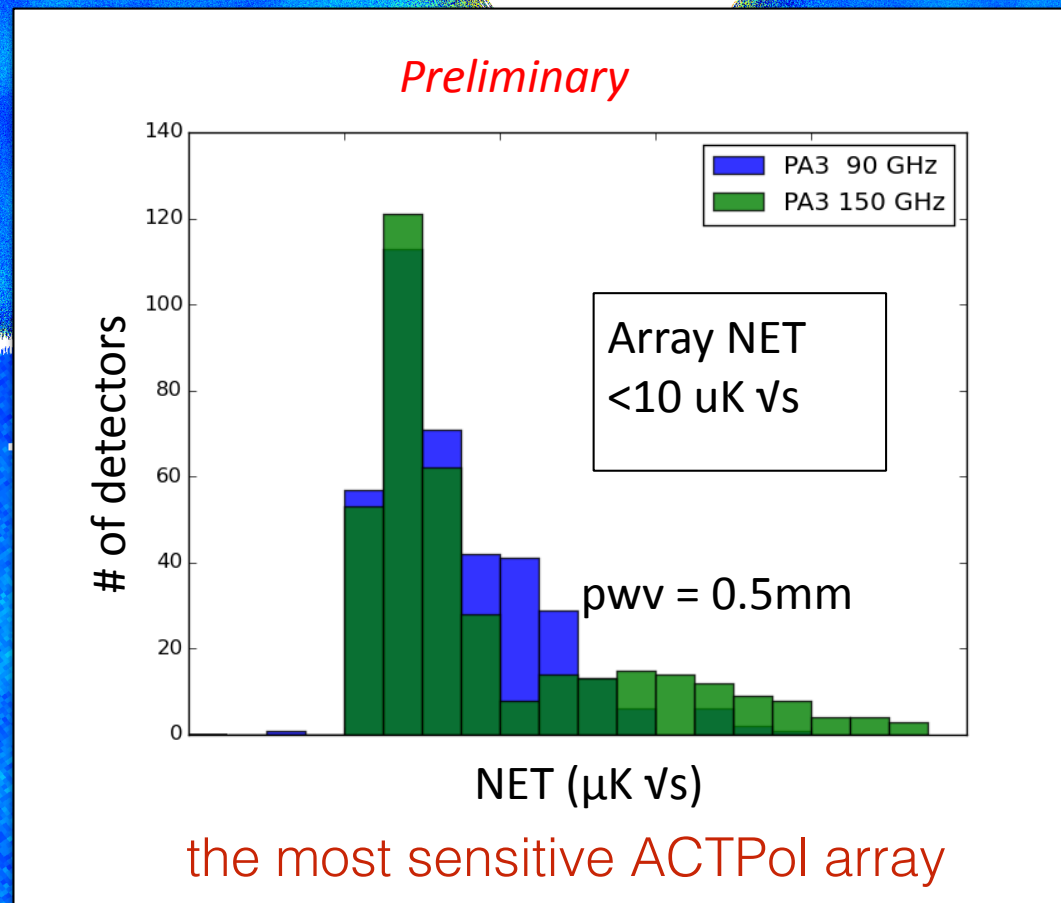
# Centaurus A with our multichroic array

ACTPol PA3: 90 GHz

ACTPol PA3: 146 GHz

Planck

3 GHz





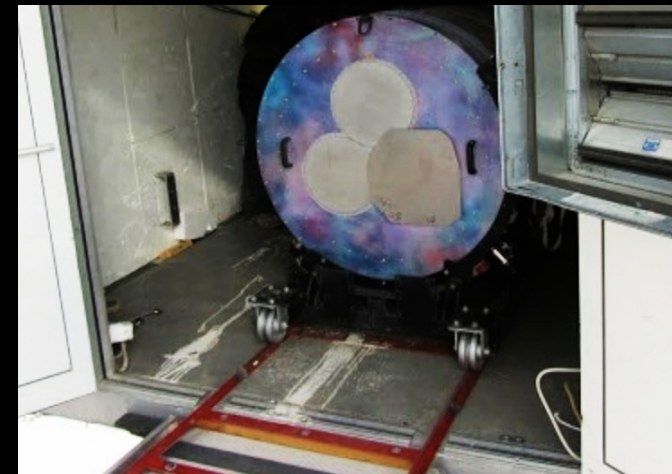
# ACTPOL STATUS



- 2013:** First array (all 146 GHz)
- background limited
  - consistent with proposed sensitivity
  - first results published

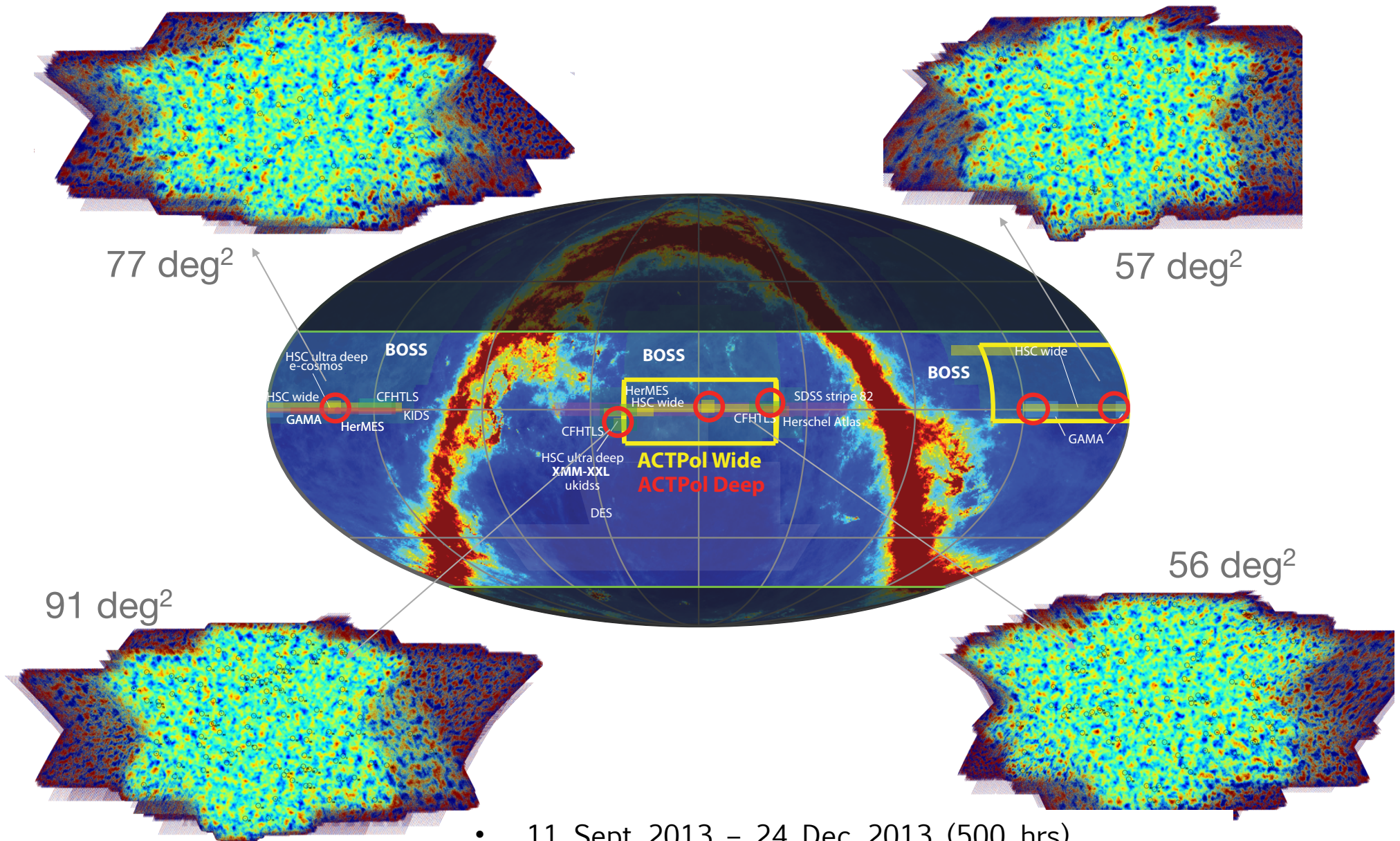
- 2014:** Two arrays (all 146 GHz)
- analysis underway

- 2015:** Multichroic 90/146 GHz
- First light Feb 2015
  - **First fielded multichroic polarimeter array**





# ACTPol Survey 2013



- 11 Sept 2013 – 24 Dec 2013 (500 hrs)
- Only one 150 GHz array installed then
- Four ~ 70 deg<sup>2</sup> patches





# PLANCK

high-pass filtered at  $l = 200$

**$\sim 30 \text{ deg}^2$**



The image is a grayscale astronomical field, likely from the ACTPol survey. It shows a dense distribution of celestial objects, including numerous bright stars and several faint, diffuse galaxies. The background is a noisy, grainy texture. In the top right corner, the text 'ACTPol' is written in a bright cyan color. In the bottom left corner, there is a text label 'high-pass filtered at l = 200'. In the bottom right corner, there is a text label '~30 deg²'.

high-pass filtered at  $l = 200$

**~30 deg<sup>2</sup>**



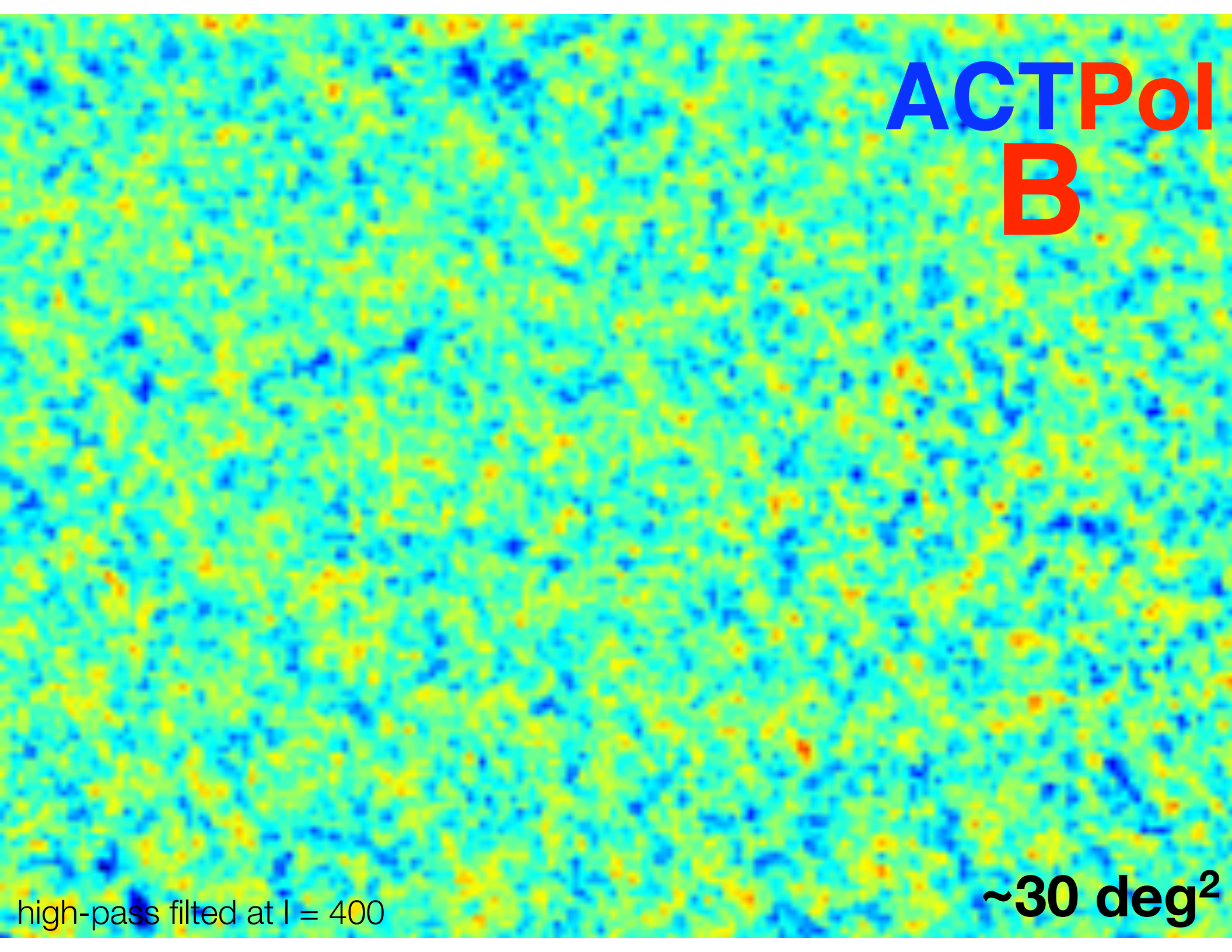


ACTPol  
E

high-pass filtered at  $l = 400$

$\sim 30 \text{ deg}^2$



The image is a full-frame astronomical observation, likely a deep field, showing a dense distribution of galaxies. The color map indicates intensity or flux, with blue representing lower values and yellow/orange representing higher values. The galaxies are mostly oriented horizontally, suggesting a selection effect or a specific orientation in the field. The background is filled with a complex pattern of noise and faint galaxy features.

ACTPol  
B

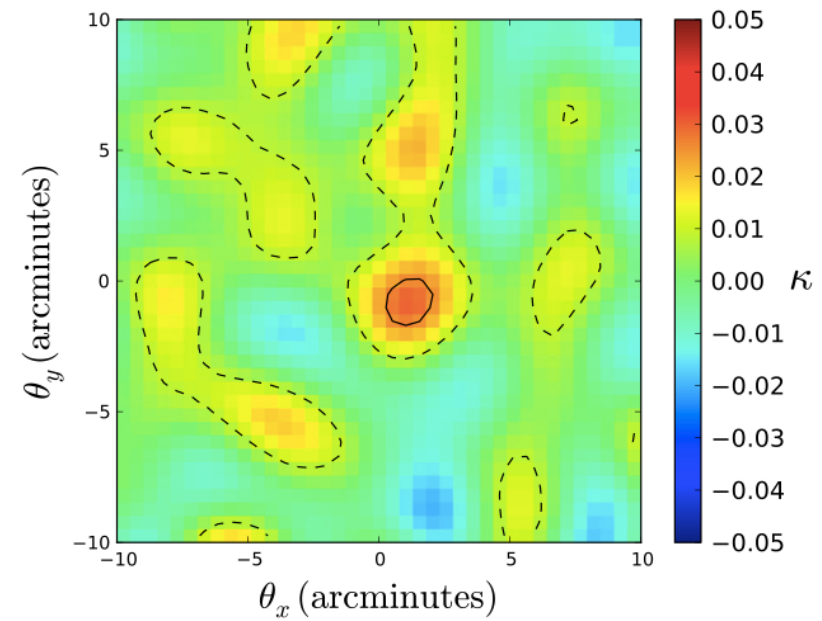
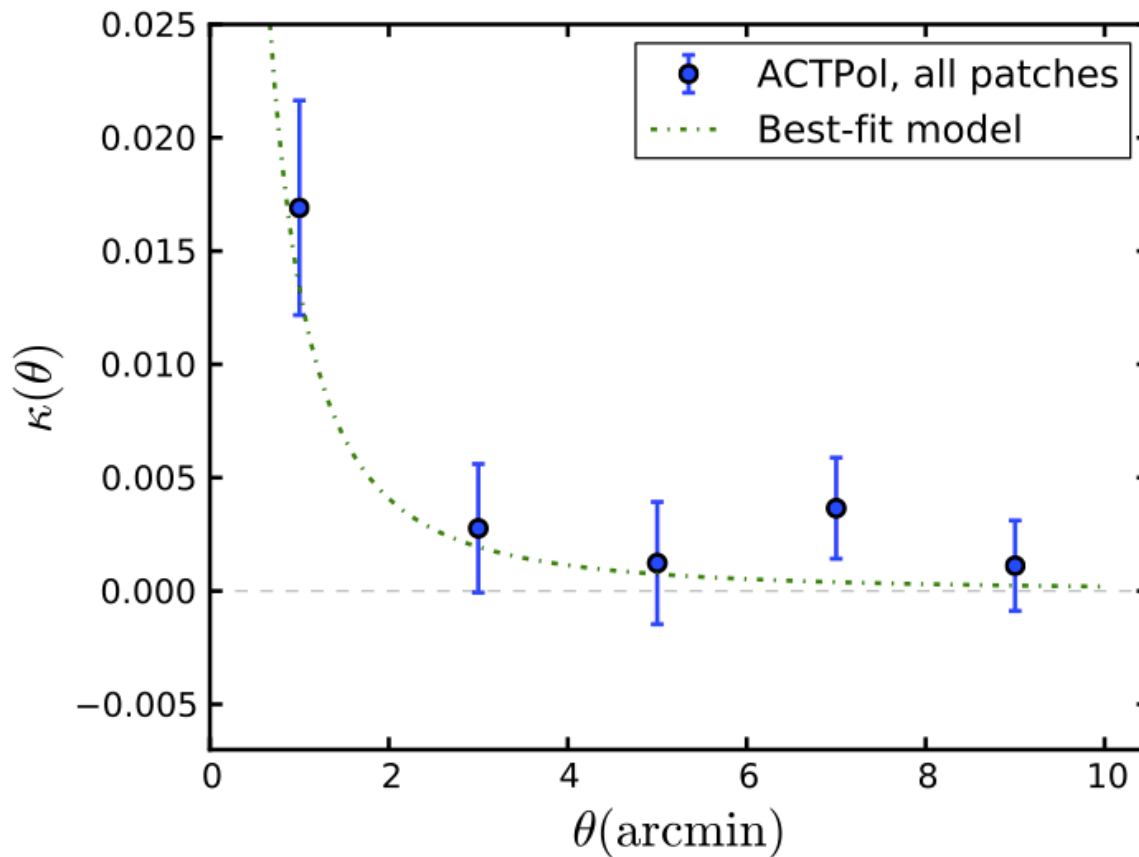
high-pass filtered at  $l = 400$

$\sim 30 \text{ deg}^2$



# CLUSTERS LENSING the CMB

$3.2\sigma$ ; stack of 12,000 CMASS galaxies (SDSS/BOSS)

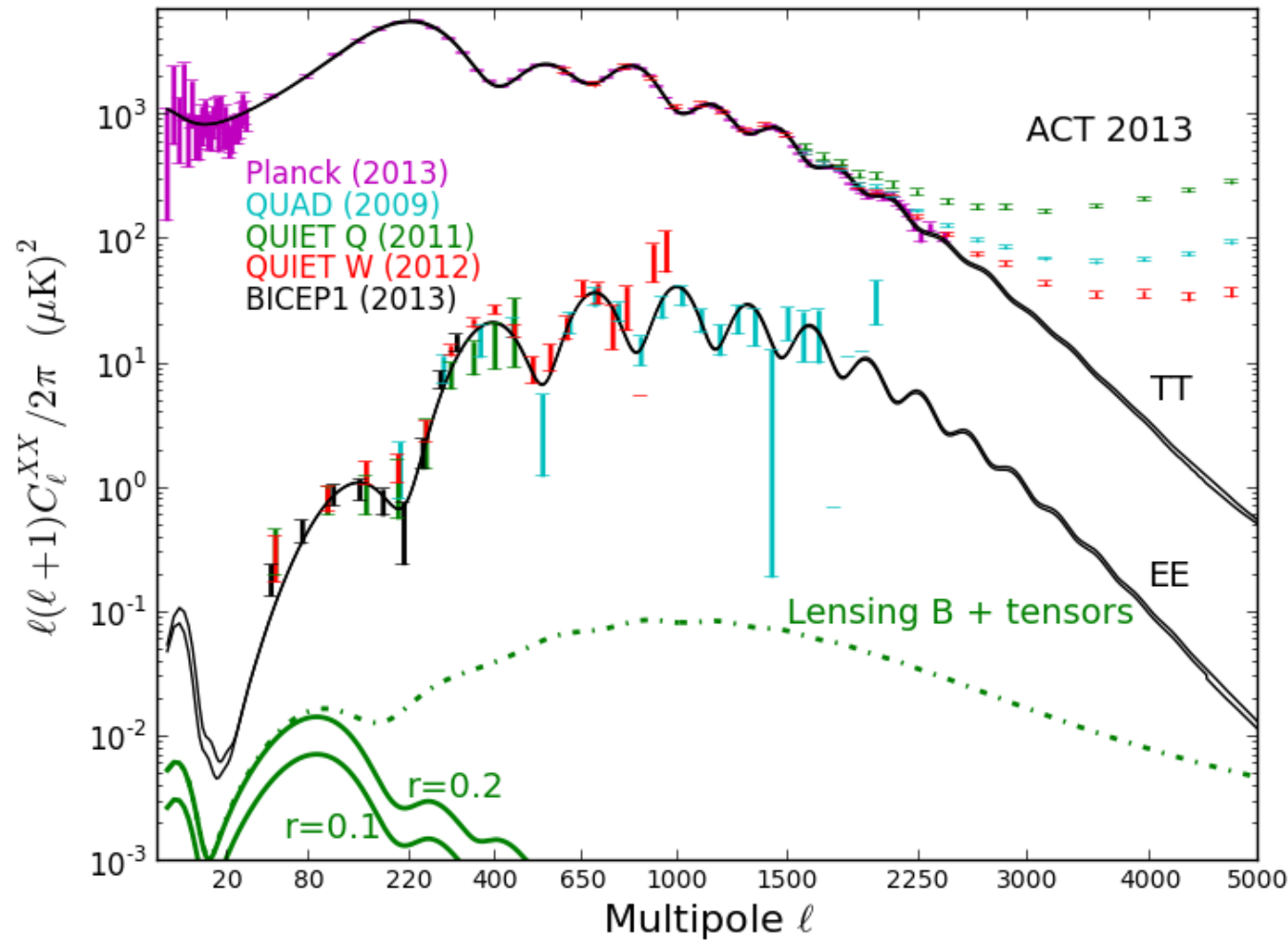


Madhavacheril et al – PRL 114, 151302, 2015. (ACTPol 2014 D1, D5, D6 fields.)



# CMB Status and Next Steps

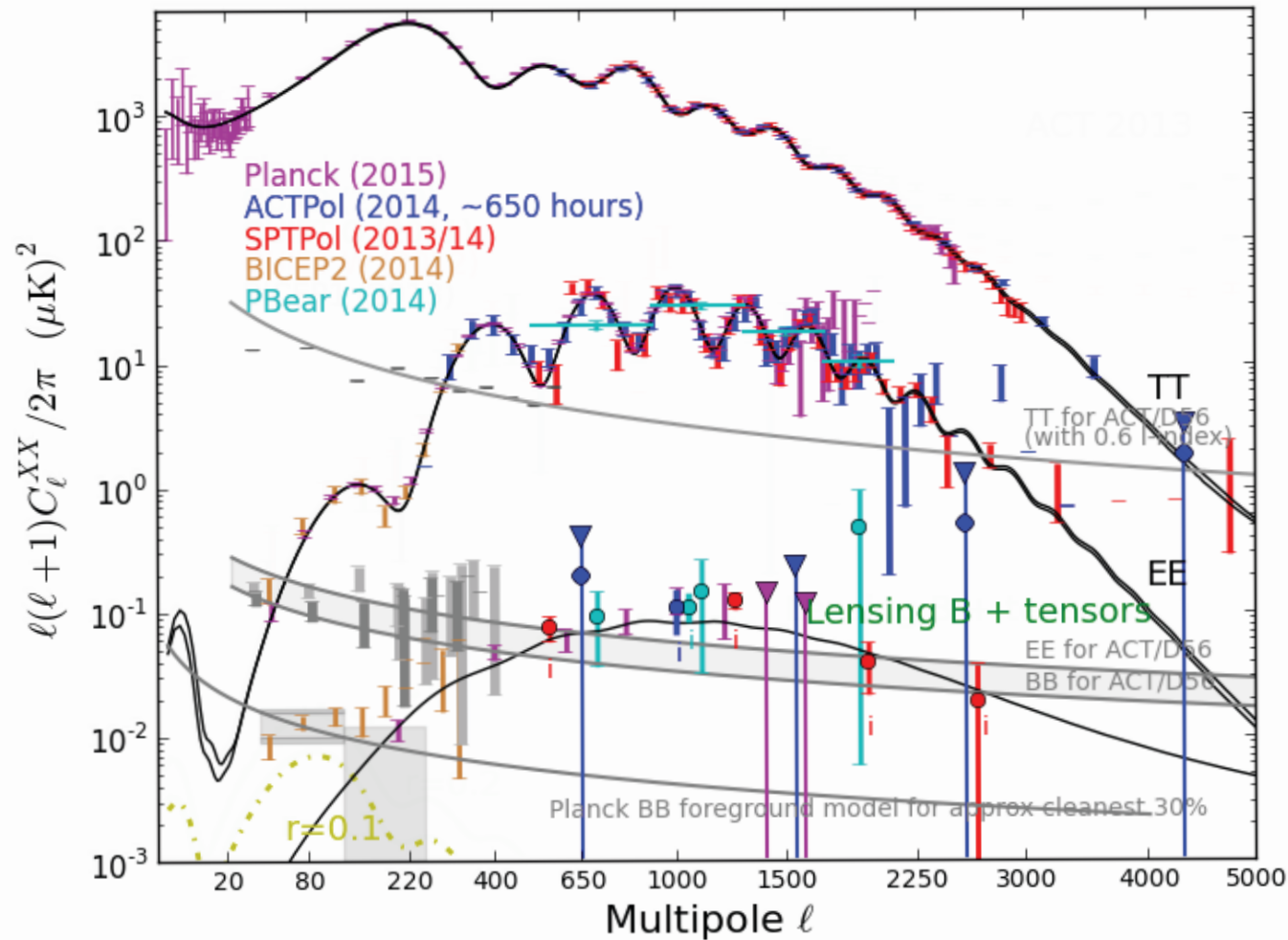
(data as of 2013)





# CMB Status and Next Steps

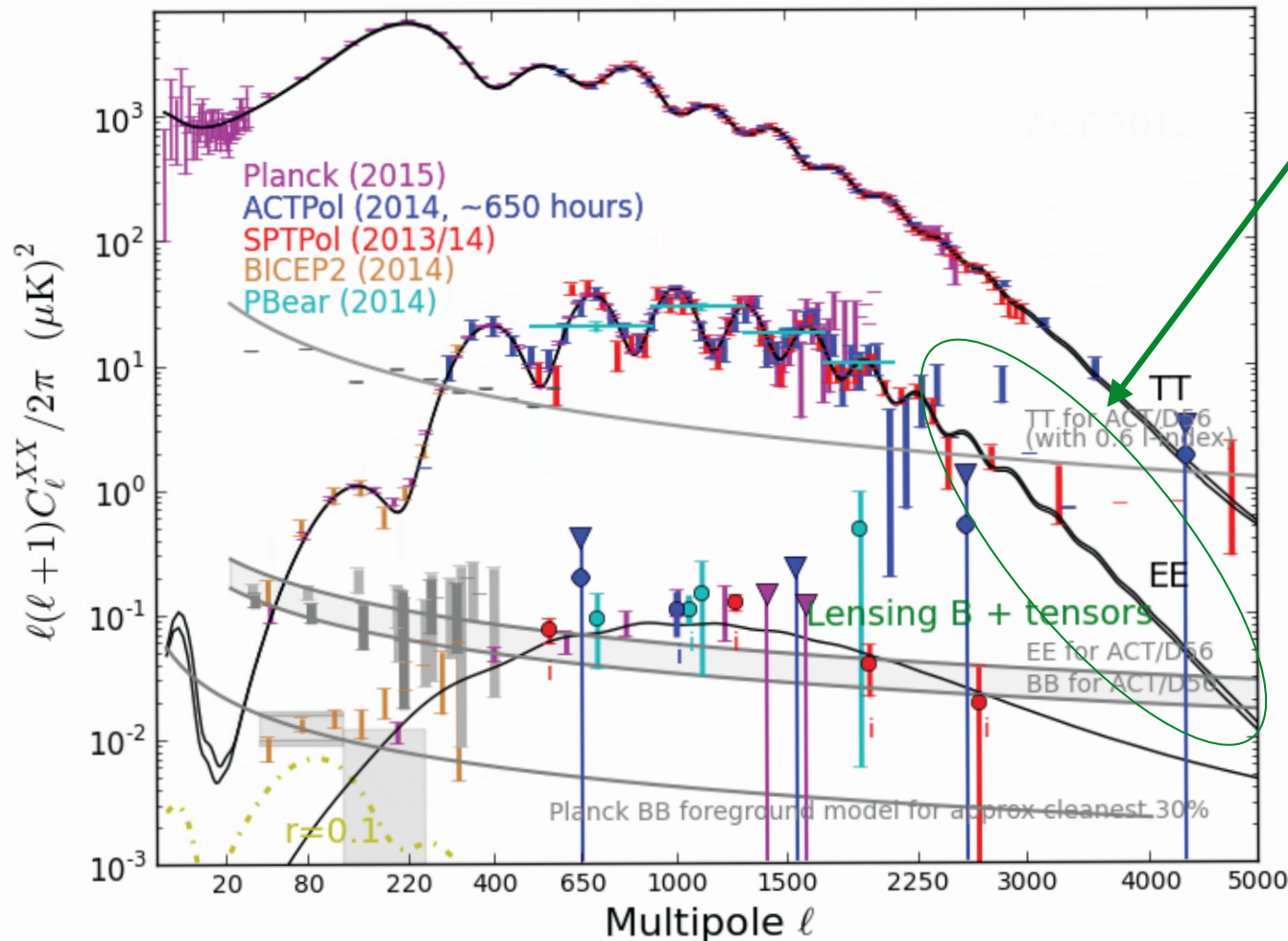
(data as of March 2015)





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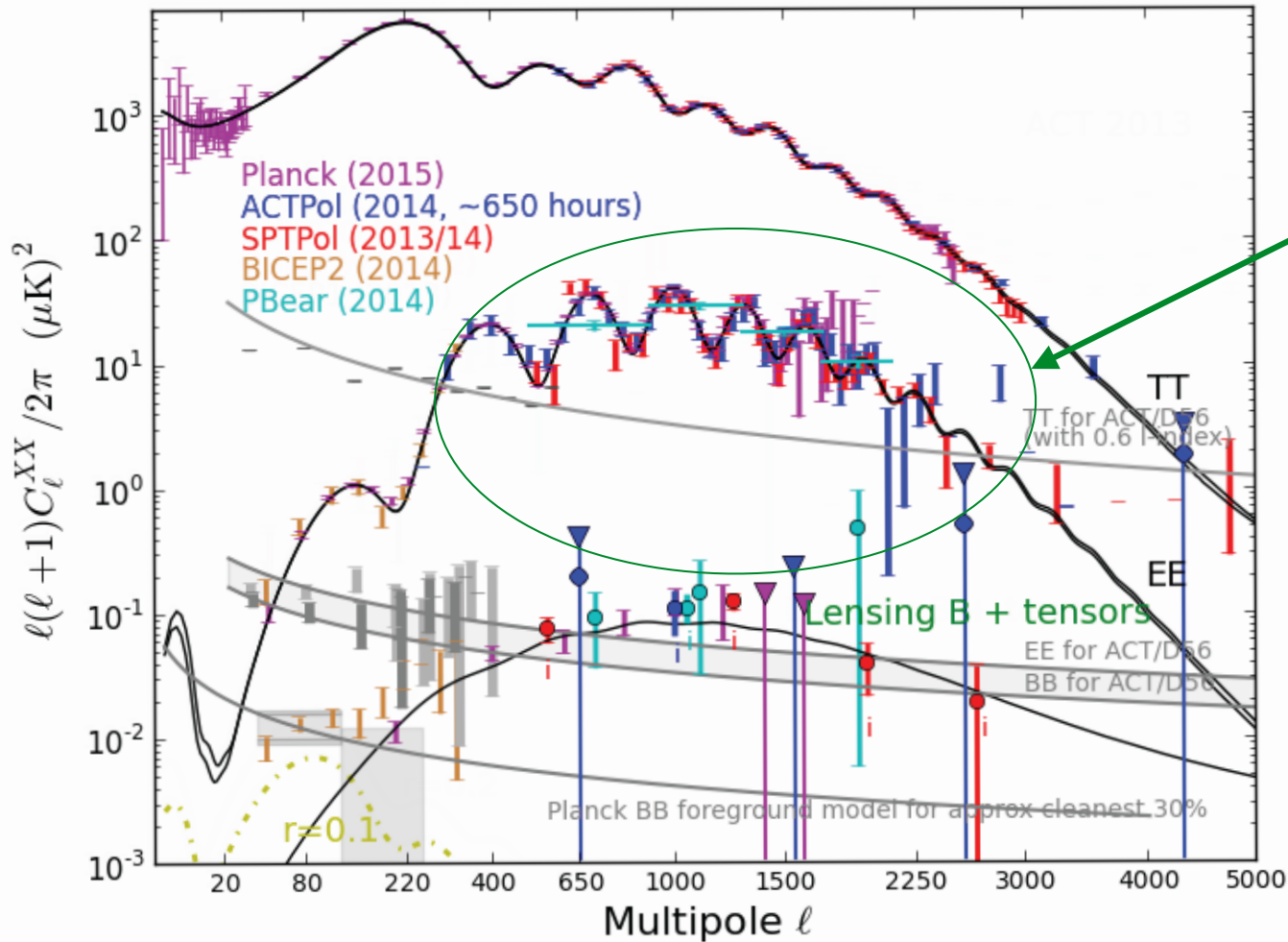


- **damping tale**
  - $N_{\text{eff}}$ ,  $n_s$ ,  $Y_{\text{He}}$
- **EE spectrum**
  - improved standard cosmology
- **Lensing**
  - $\Sigma m_\nu$ , dark energy, dark matter
- **Large Scale B**
  - inflationary gravitational waves



# CMB Status and Next Steps

(data as of March 2015)

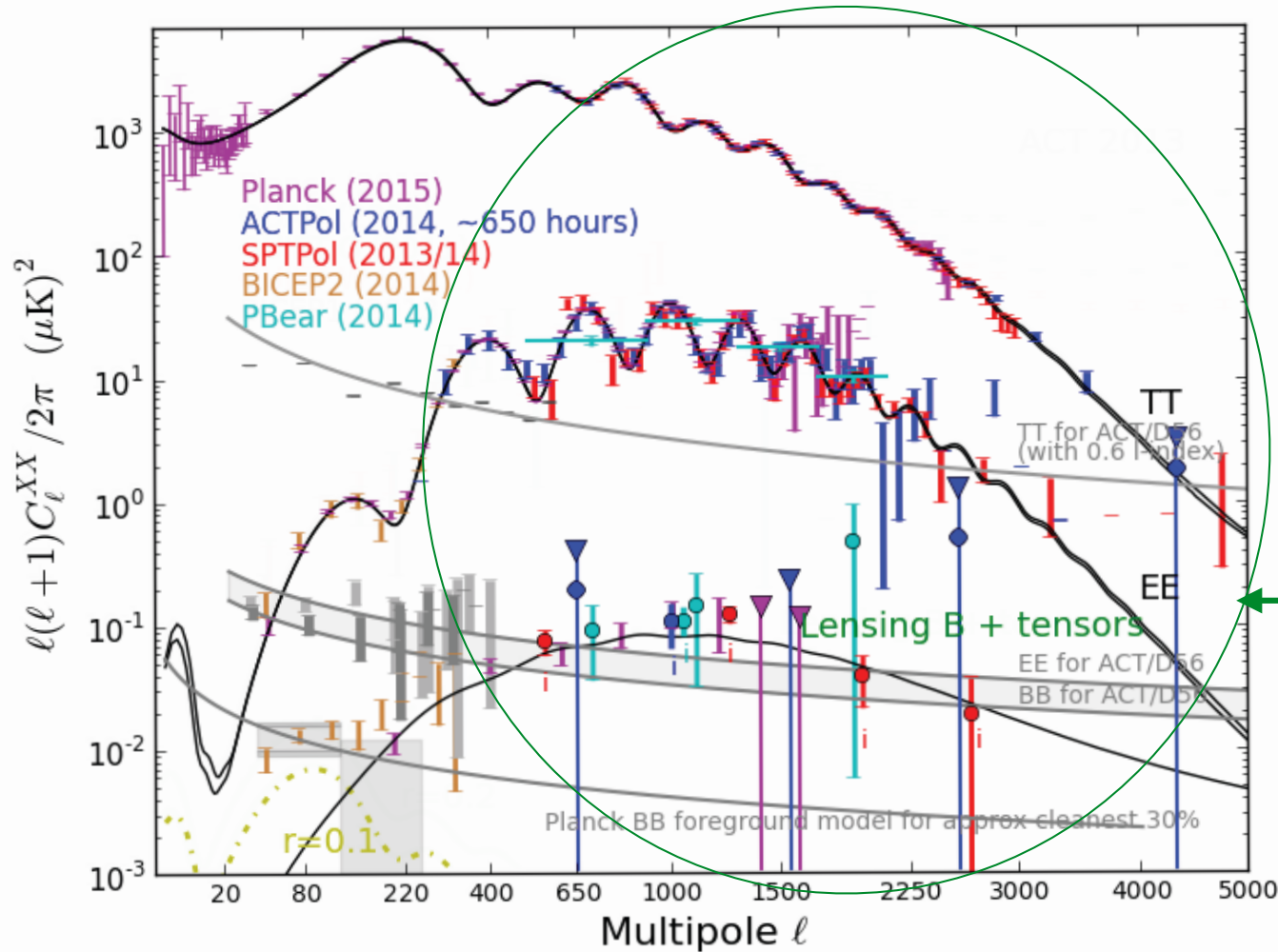


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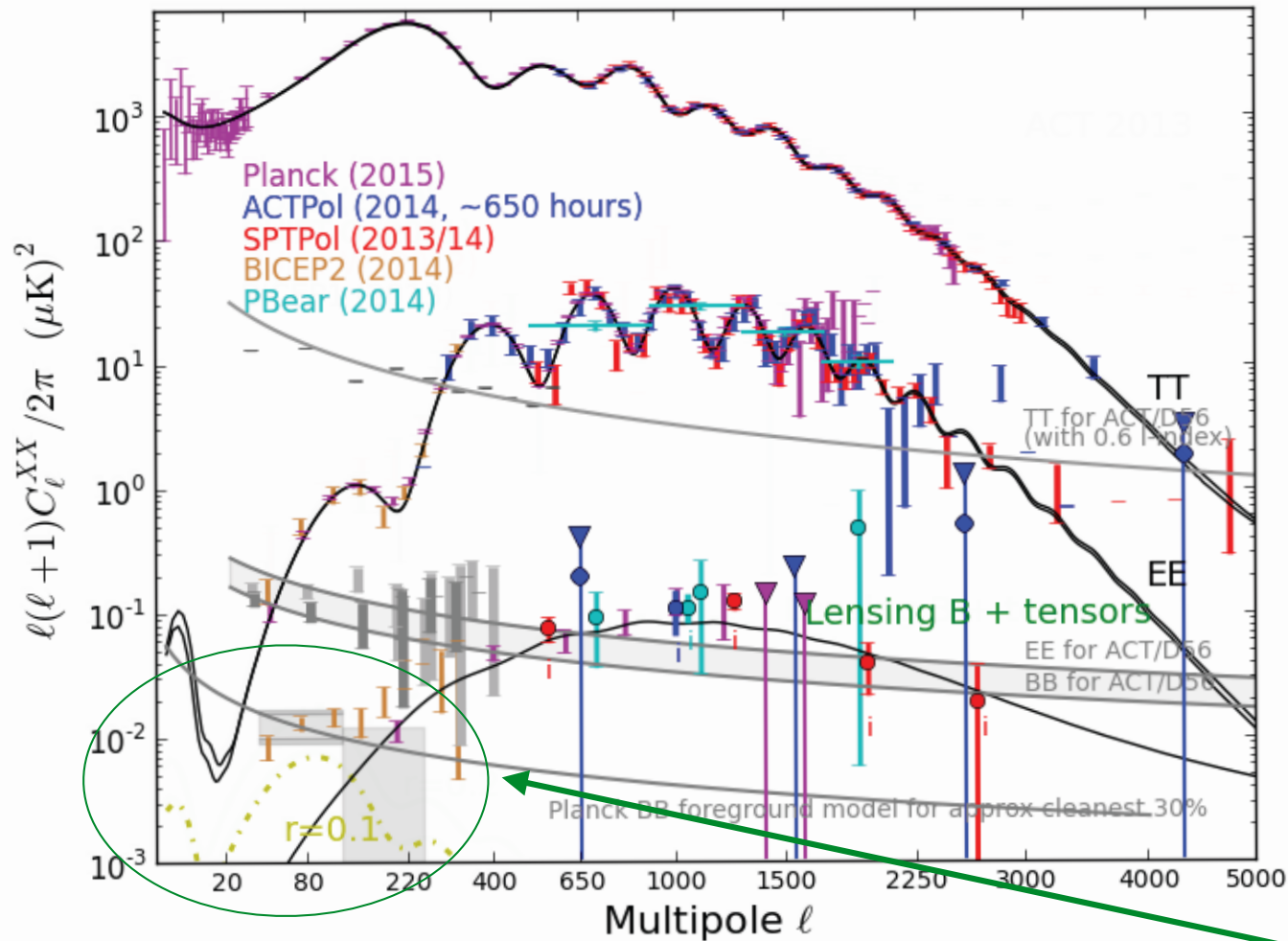
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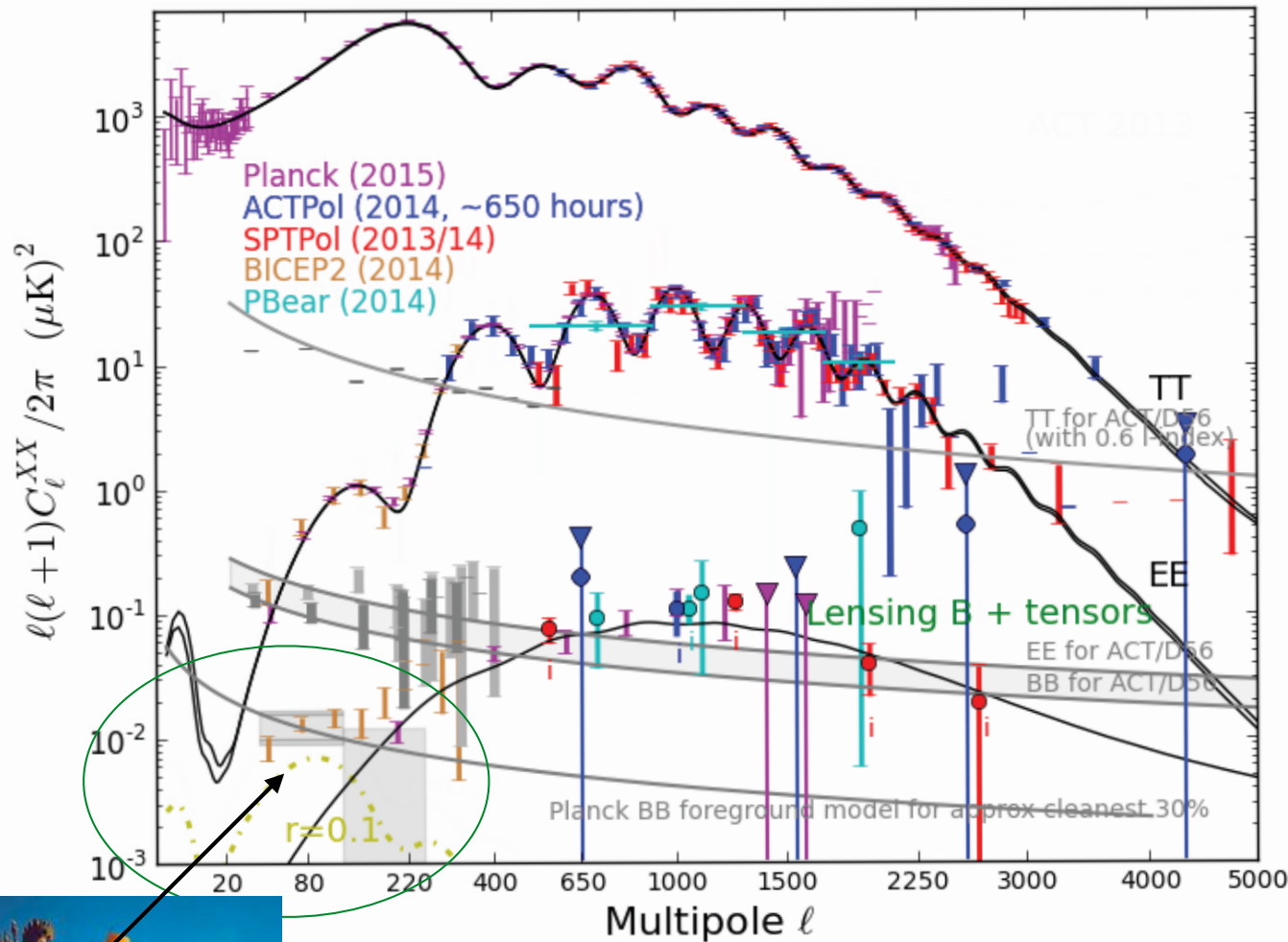


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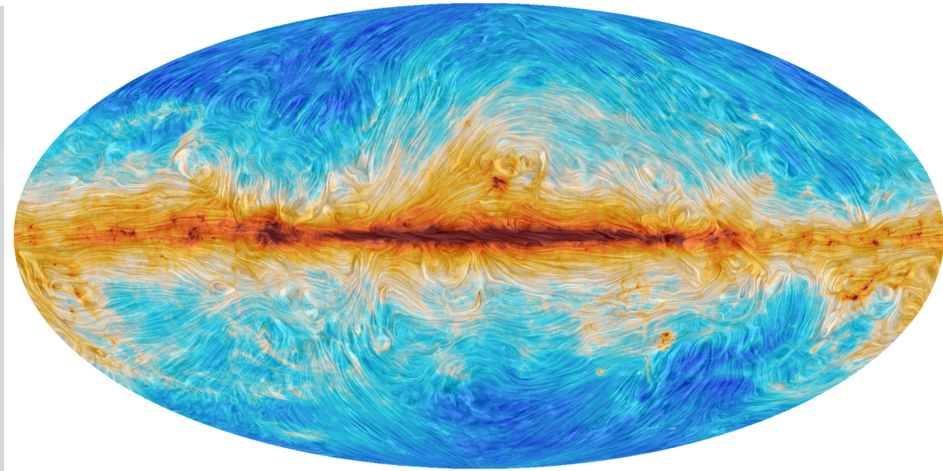


- **damping tail**
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# CMB Status and Next Steps

Planck 353 GHz  
(Dust)





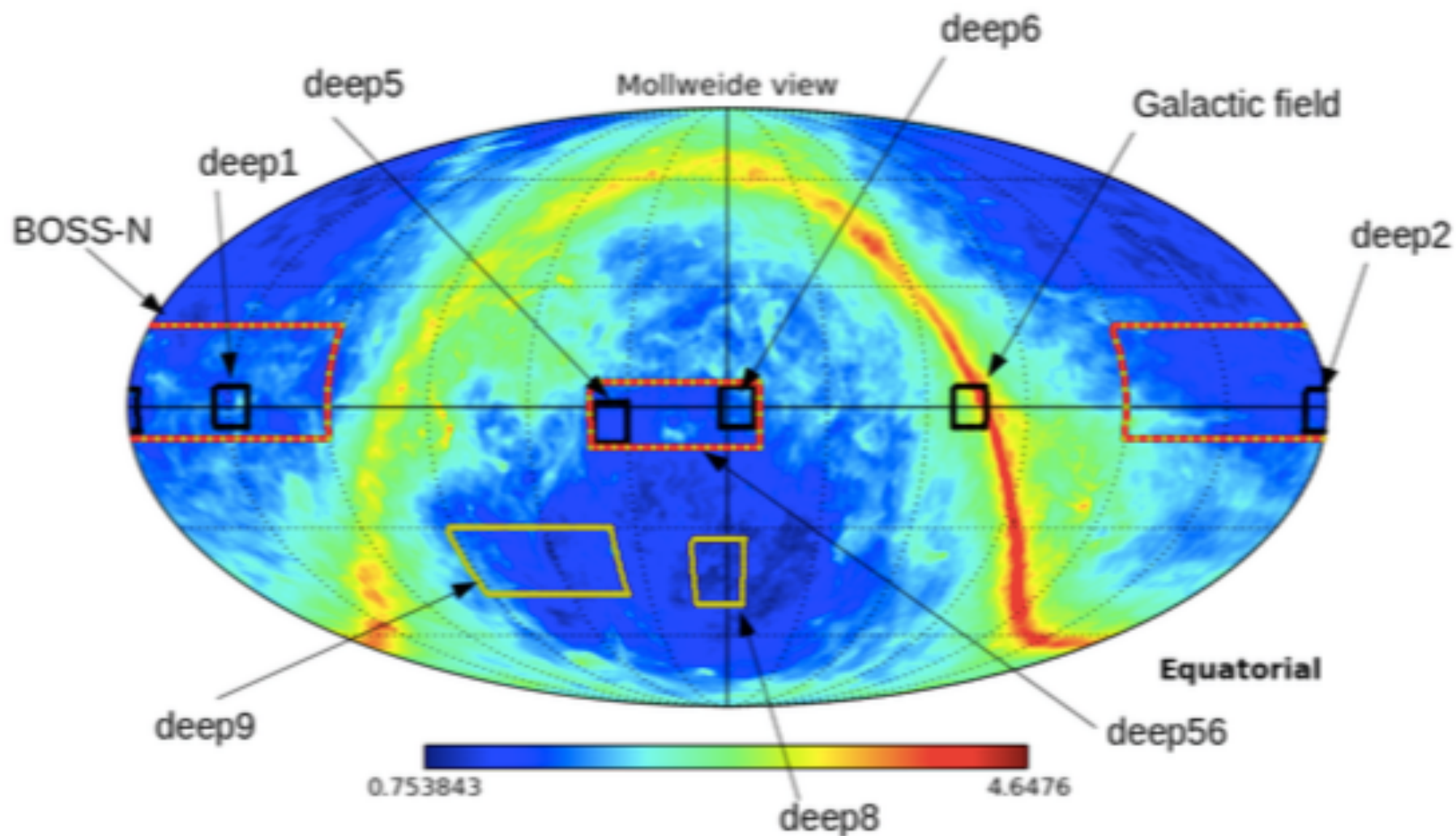
# What is required to get all this science

- More sky area
- lower noise
- multiple frequencies

# Full ACTPol survey

2014 & 2015

- Data already complete
- ~2000 square-degrees (BOSS N)
- ~600 square-degrees (deep 5-6)





# The Near Future: ACTPol Data Analysis

## preliminary results

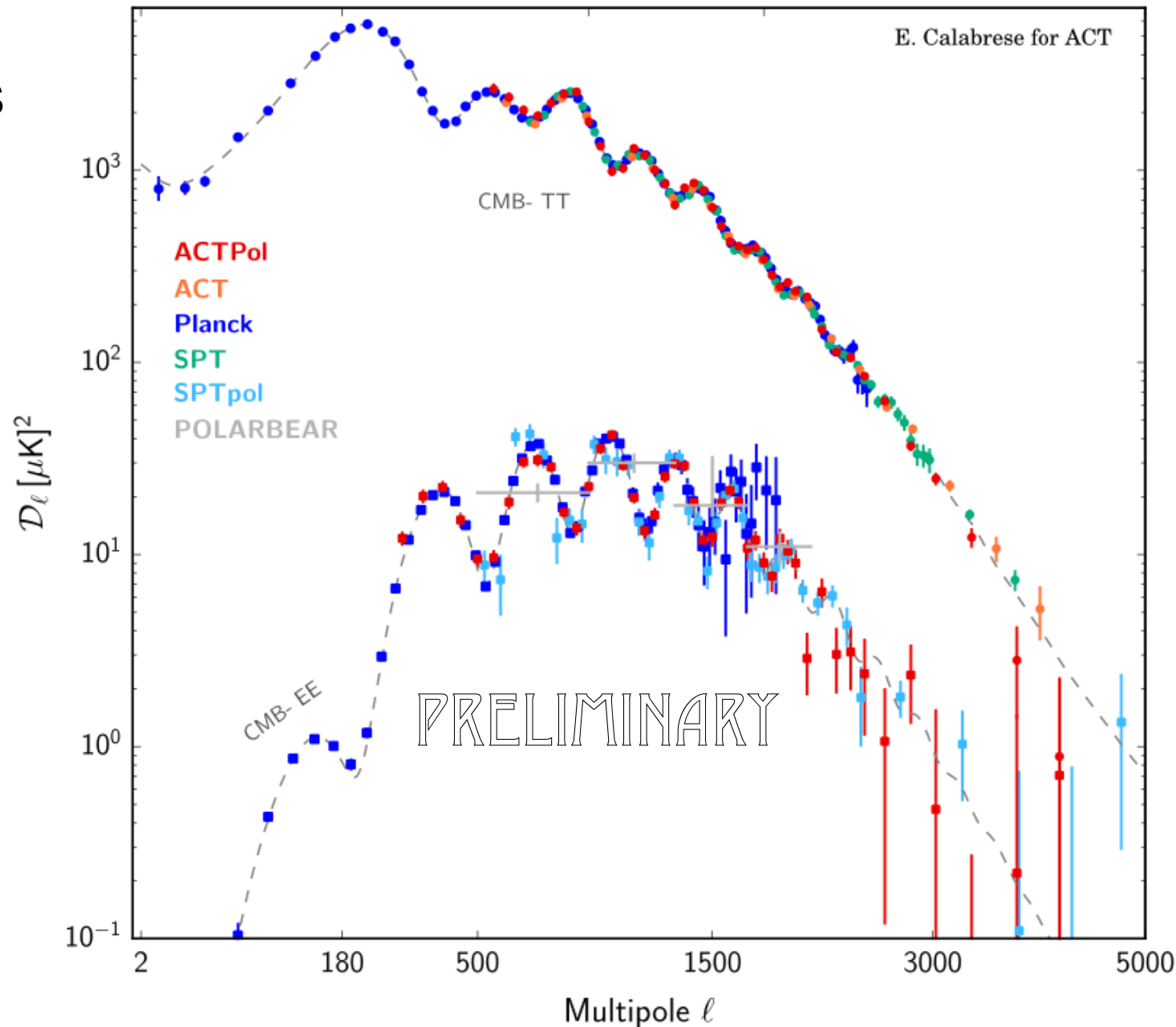
D56 Field

(12% of the ACTPol data)

$\sim 650 \text{ deg}^2$ , @  $\delta \sim -3^\circ$ , RA  $\sim 15^\circ$

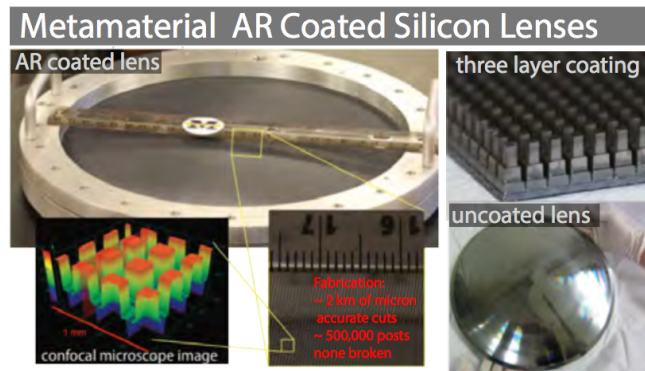
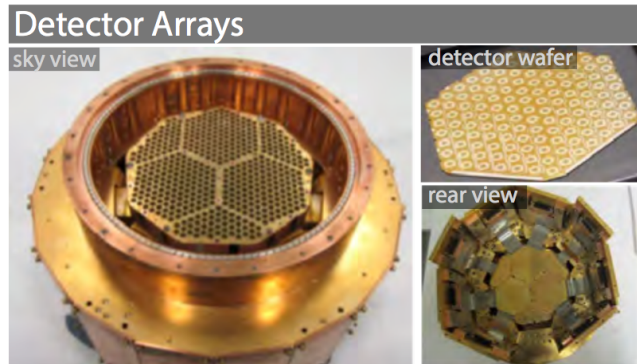
## up next:

- (1) lensing, SZ, and cross correlations with this map
- (2) analyze the rest of 2014 and all of 2015



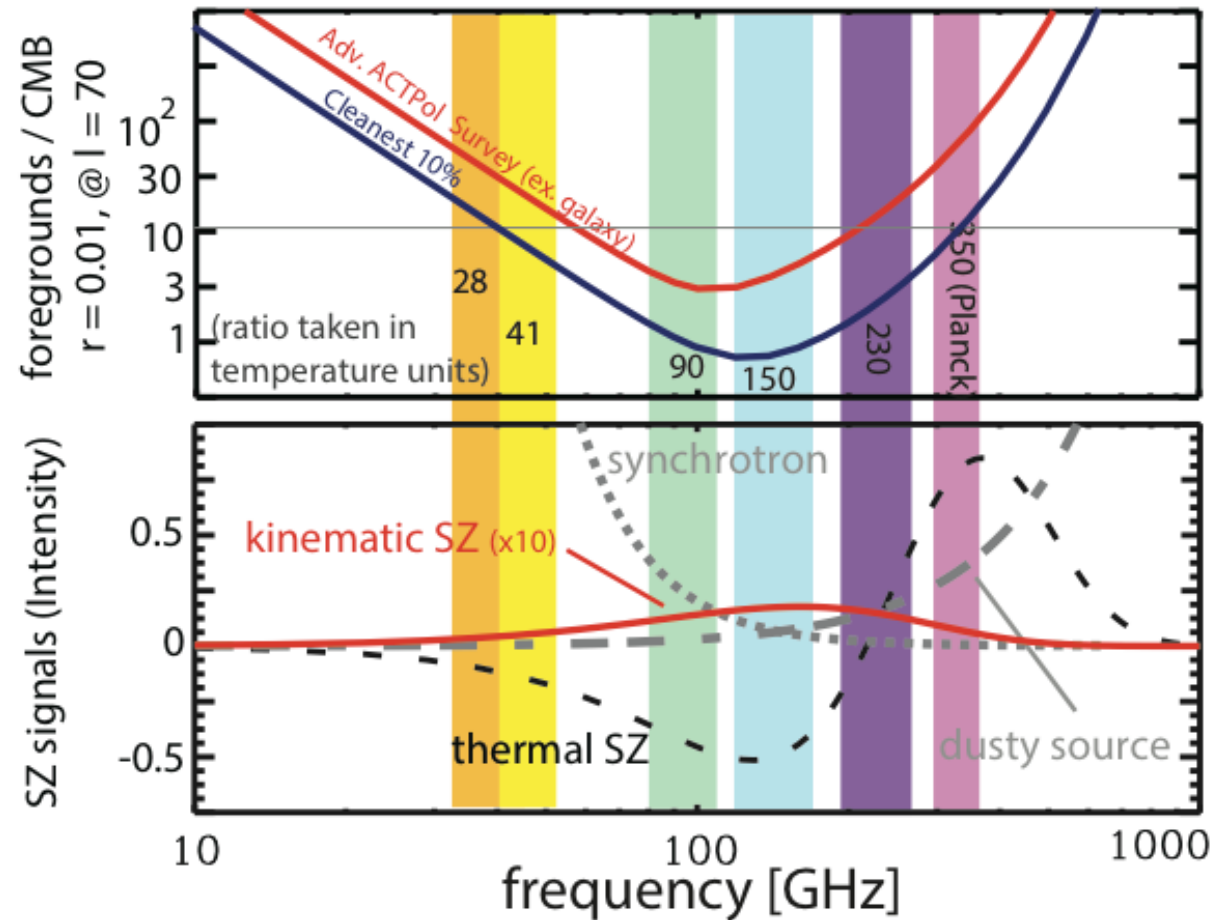
# Advanced ACTPol

based on ACT technology



5 frequency bands

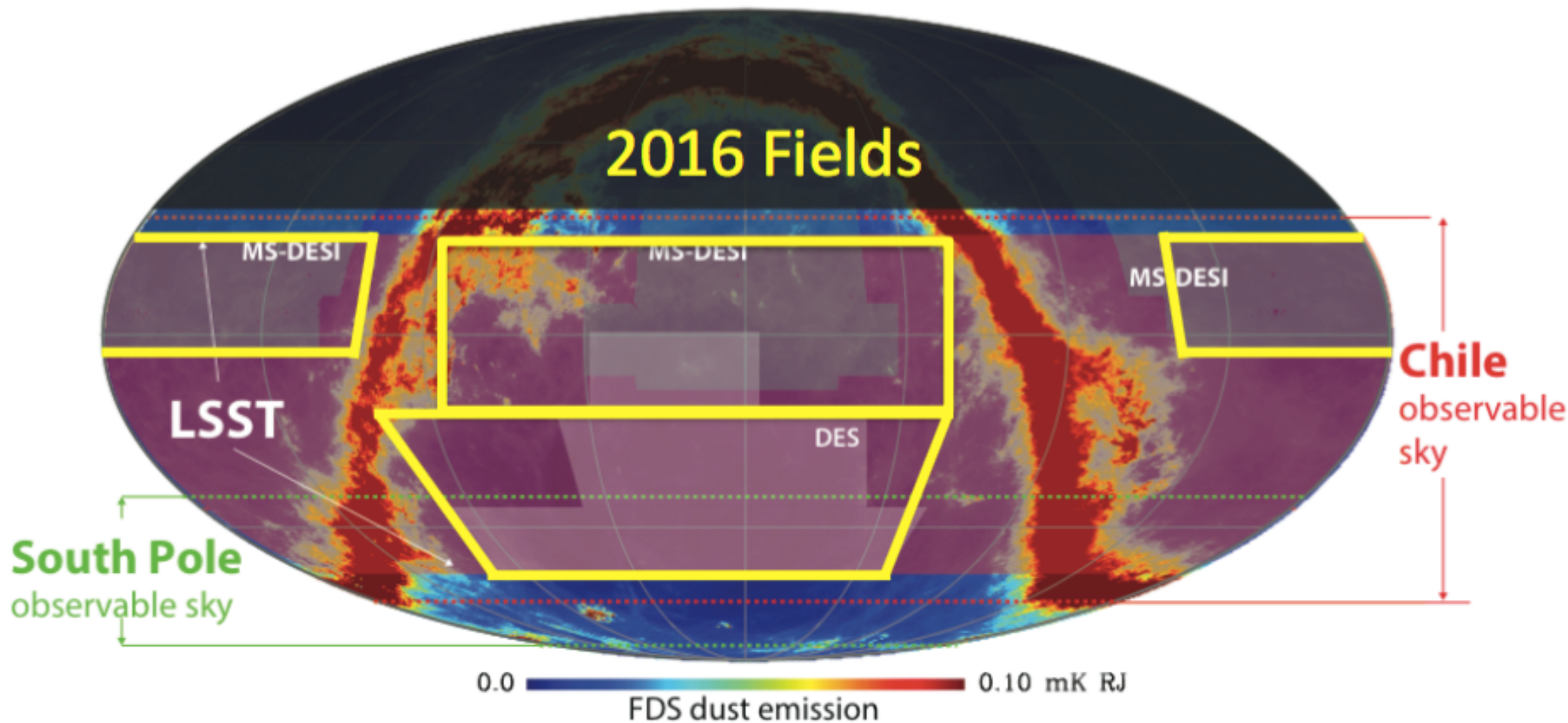
## Foreground Removal





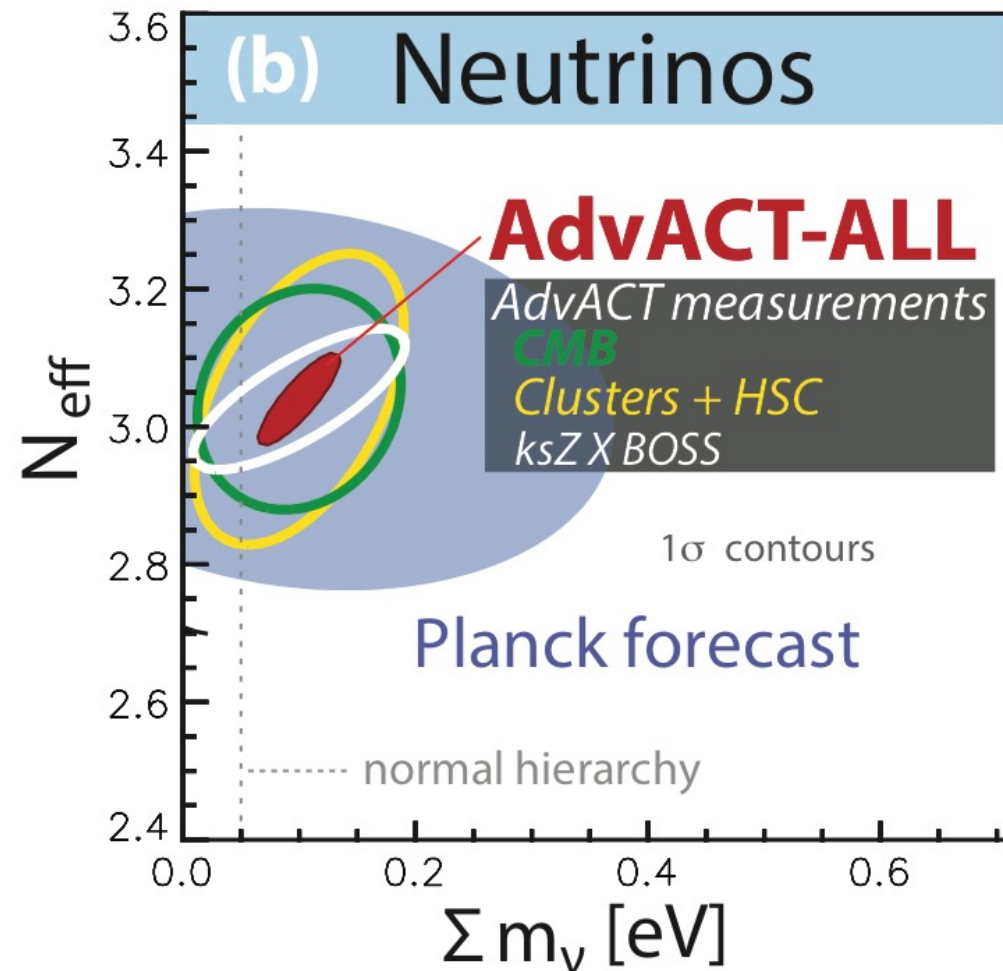
# The Future Starts ~Now:

## Advanced ACTPol Survey: 2016-2018

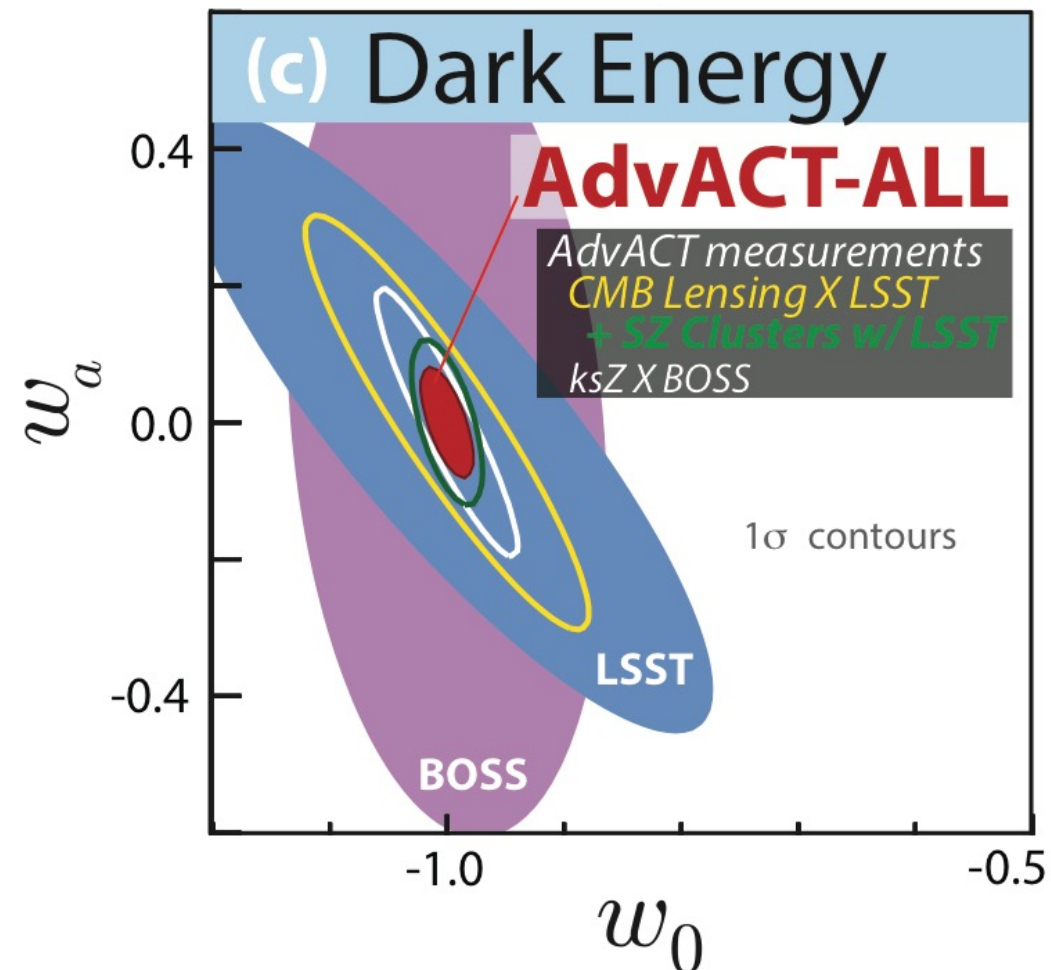


# Cross Correlation Projections

Projected to improve Planck limit on  $\Sigma m_\nu$  by 10x!



Projected to improve LSST's DE FOM by 20x!



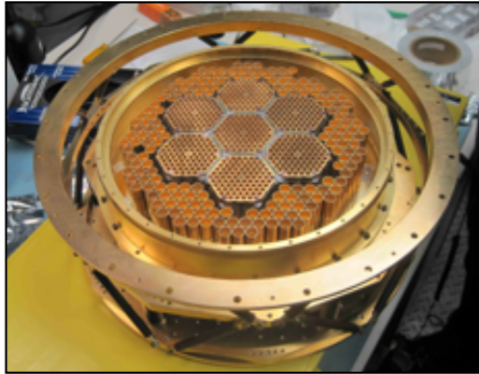


***Maintaining Moore's Law: focal planes are saturated so must use parallel processing and multiple telescopes.***

Stage II **ACTPol / SPTPol**

**Now**

~1000 detectors

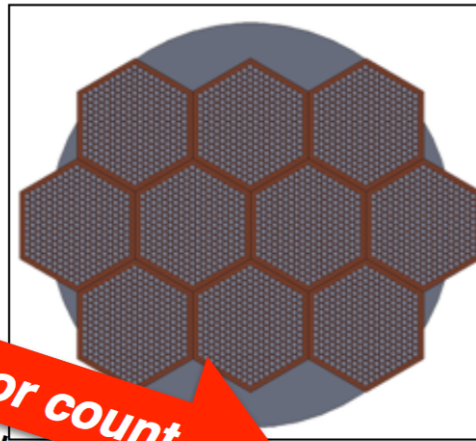


**Advanced ACTPol  
SPT 3G**

Stage III

**ramping up**

~10,000 detectors

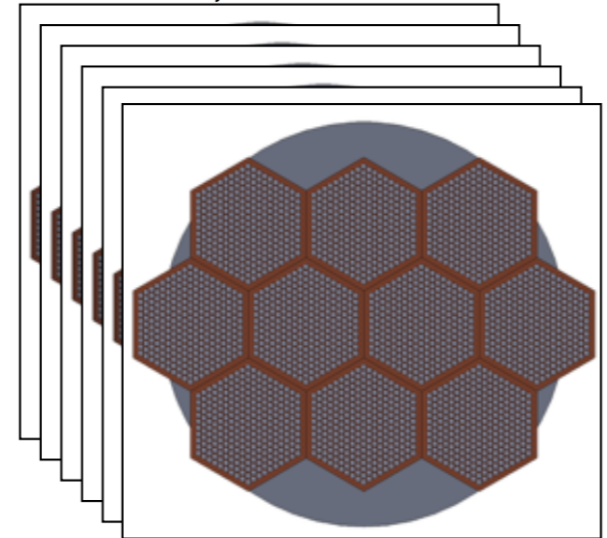


**increasing detector count**  
(the trend being followed by all  
CMB projects, not just SPT)

Stage IV

**~2020 - CMB-S4**

~500,000 detectors



**CMB-S4: A program to put  $O(500,000)$  detectors spanning 30 - 300 GHz using multiple telescopes and sites to map  $\geq 70\%$  of sky.**

## Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context



Report of the Particle Physics Project Prioritization Panel (P5)

May 2019

# P5's timelines

CMB-S4  
ramps up  
as  
LSST  
ramps down





# First CMB-S4 Community Meeting (Sept 2015) at the University of Michigan





# The Simons Observatory

<http://simonsobservatory.org>

- A five year, \$45M+ program to pursue key Cosmic Microwave Background science targets, and advance technology and infrastructure in preparation for CMB-S4.
- Merger of the ACT and POLARBEAR/Simons Array teams.
- Tentative plans include:
  - Major site infrastructure
  - Technology development (detectors, optics, cameras)
  - Demonstration of new high throughput telescopes.
  - CMB-S4 class receivers with partially filled focal planes.
  - Data analysis

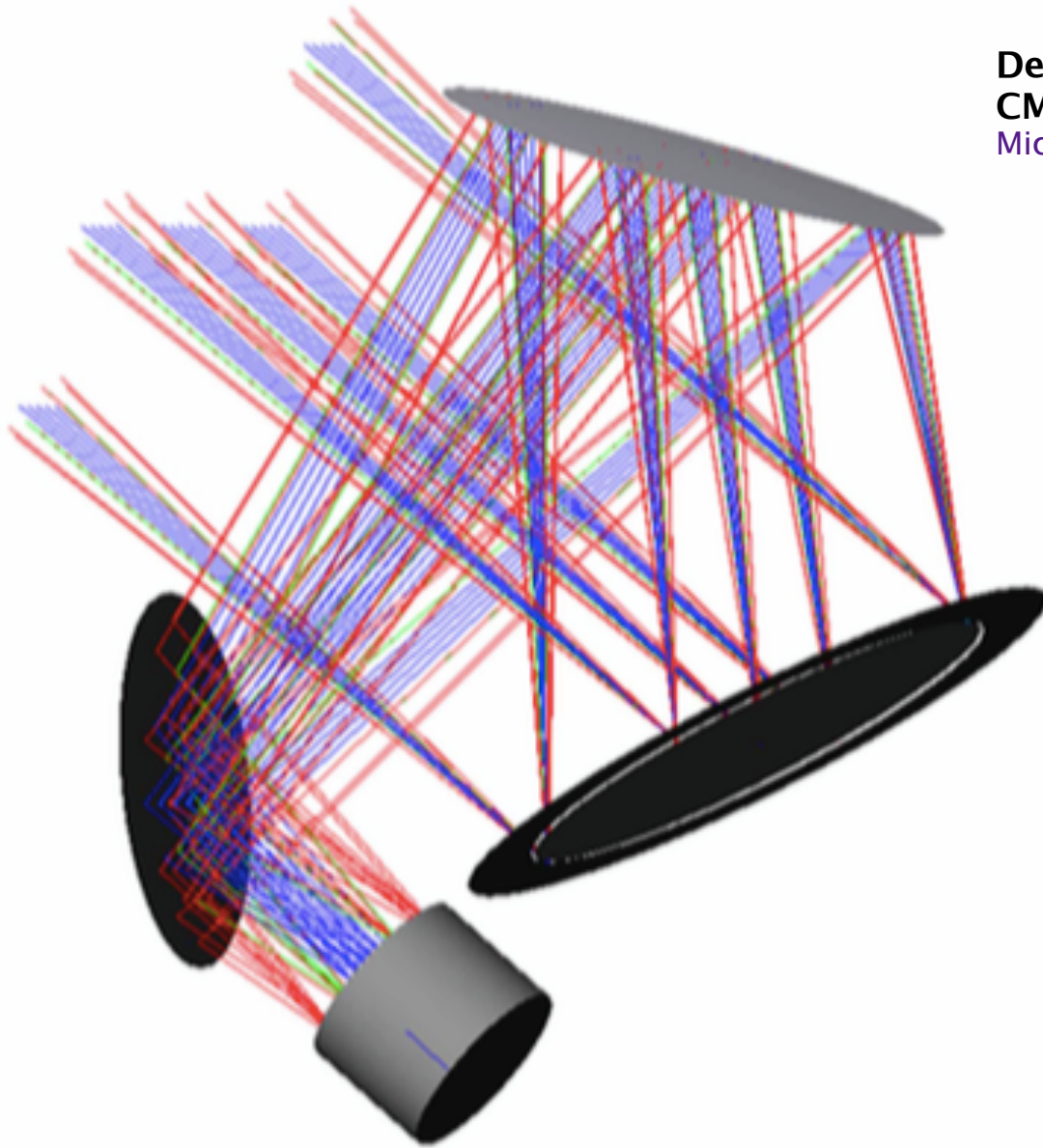
**POLARBEAR/Simons Array**

**ACT**





# 6-m telescope with 100,000 detectors



Designs for a large-aperture telescope to map the CMB 10X faster

Michael D. Niemack submitted to Applied Optics

